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Safety Risk Assessment Methodologies – the Hi Fly Operator Case

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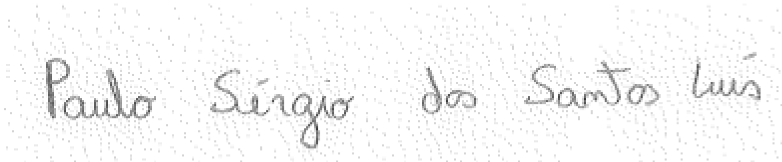

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Dedicatory

To my family.

"There is no greater thing you can do with your life and your work than follow your passions – in a way that serves the world and you".

Richard Branson

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To my girlfriend, for all the patience, help and crazy things together. We’ve made it.

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Resumo

Esta dissertação surge devido ao constante crescimento da indústria da aviação e com isto um aumento à exposição aos perigos e riscos. Este aumento, provoca a crescente necessidade de criar, implementar e melhorar os sistemas de gestão de risco por parte de operadores aéreos, aeroportos e empresas de manutenção de forma a garantir a segurança das operações, passageiros, tripulações e trabalhadores.

Esta dissertação foca-se na escolha de um método de análise de risco que seja o mais adequado às operações da Hi Fly. O método tem de cumprir com toda a legislação em vigor e padrões impostos pela Hi Fly. Para tal, foi feita uma análise bibliográfica dos métodos de análise de risco adequados à aviação. Esta análise inicia-se com a descrição do sistema de gestão de risco proposto pela organização da aviação civil internacional. Em seguida, é descrito o processo, a estrutura e os objetivos de cada método de análise de risco.

Para a escolha do método mais adequado às operações da Hi Fly é utilizado a metodologia de análise de decisão multicritério, mais concretamente a metodologia MACBETH (*Measuring attractiveness by a categorical based evaluation technique*). A primeira fase para a aplicação desta metodologia consiste na criação de áreas chave de desempenho e de indicadores de desempenho. A partir destes, a segunda fase consiste na criação de um inquérito efetuado aos *Safety Links* de cada departamento da Hi Fly e aos membros que compõe o departamento de Safety desta empresa, onde as questões são adaptadas de modo que a resposta ofereça uma escala de classificação. É pedido para ordenarem cada área chave de desempenho pela sua relevância e também para responderem a cada questão numa escala de um a cinco. Para o departamento de Safety, como estão mais entrosados com os métodos de análise de risco existentes é feito outro inquérito tem como objetivo ter uma comparação entre cada método de cada indicador. A última fase consiste em atribuição de pesos às áreas chave de desempenho conforme a sua média de relevância. A avaliação é feita através da ferramenta M-MACBETH software que é um software desenhado para efetuar a metodologia MACBETH. Esta avaliação permite-nos obter o método mais adequado às operações da Hi Fly.

Os resultados do inquérito aos vários departamentos mostram que a área mais relevante numa análise de risco é a capacidade de prever o impacto e a severidade do evento bem como a criação de barreiras e controlos de mitigação. O inquérito efetuado ao departamento de Safety da empresa confirmou o resultado descrito acima. Quanto aos indicadores os resultados diferem, mas ambos concordam que o indicador menos

relevante é a frequência e qualidade das atualizações que os métodos recebem. Estes dados definem os pesos introduzidos no software e juntamente com o julgamento efetuado entre os indicadores para cada método pelos dois especialistas no departamento de Safety satisfazem os critérios necessários para a utilização do software de apoio à decisão.

Através dos dados introduzidos, a ferramenta ditou que o método de análise de risco mais adequado às operações da Hi Fly é o European Risk Classification System (ERCS).

Palavras Chave

Análise de risco; Análise Multicritério; Metodologia BowTie; Operador aéreo; Segurança; Sistemas de gestão de risco.

Resumo Alargado

Motivação

O setor da aviação está em constante crescimento. De acordo com a ICAO (Organização da Aviação Civil Internacional), em 2030 prevê-se que descolem e aterrem 200 000 voos comerciais diariamente em todo o mundo, quase o dobro dos voos atualmente. Com mais voos, aumenta a exposição a perigos e riscos, o que pode levar a um aumento do número de acidentes/incidentes, daí a necessidade de garantir a segurança de todas as operações, passageiros, tripulações e pessoal.

Sublinhando a importância de gerir esta exposição, em 2015, o presidente da IATA (Associação Internacional do Transporte Aéreo) Calin Rovinescu afirmou que a segurança é a prioridade número um na aviação. A segurança é, segundo a ICAO, "o estado em que os riscos associados à aviação, às atividades relacionadas com a operação de aeronaves ou em apoio direto à mesma, são reduzidos e controlados para um nível aceitável". Os processos de gestão do risco são implementados na indústria aeronáutica para mitigar o risco decorrente dos vários perigos associados ao voo, começando pelos fabricantes de aeronaves, aeroportos, prestadores de serviços e operadores de aeronaves. Em 2006, a ICAO exigiu que a maioria dos operadores da aviação comercial implementasse um SMS (Sistema de Gestão da Segurança).

O quadro do SMS da ICAO é constituído por quatro componentes e doze elementos, devendo a sua aplicação ser proporcional à dimensão da organização e à complexidade dos serviços prestados.

Os quatro pilares principais de um SMS são a política e os objetivos de segurança, a gestão dos riscos de segurança (SRM), a garantia da segurança e a promoção da segurança. A avaliação dos riscos é o principal elemento da SRM e é utilizada para avaliar os perigos, a gravidade e a probabilidade do risco. É fundamental para garantir a segurança na aviação porque envolve muitos perigos potenciais que podem resultar em acidentes ou incidentes graves. Ao efetuar uma avaliação exaustiva dos riscos, os operadores aéreos podem identificar e mitigar os riscos antes que eles se tornem perigosos, aumentando a segurança em todos os voos.

Objeto e Objetivos

Esta dissertação tem dois objetivos, um principal e outro secundário. Tal como o título desta dissertação sugere, o principal objetivo desta dissertação é encontrar o processo de análise e gestão dos riscos mais adequado às operações da Hi Fly. O objetivo secundário é que esta dissertação sirva como modelo para futuros trabalhos e investigações na área de análise e gestão de riscos associados aos vários setores da indústria aeronáutica (operadores aéreos, empresas de manutenção, aeroportos, etc...).

De uma forma geral, todos os capítulos desta dissertação permitiram alcançar os objetivos propostos. O segundo capítulo (estado de arte) reflete a concretização do objetivo secundário com a descrição dos vários modelos atualmente utilizados na indústria, enquanto o quarto capítulo explicita como foi atingido o principal objetivo desta dissertação com a introdução da Análise Multicritério (MCDA).

Metodologia

O desenvolvimento deste estudo divide-se em três fases.

A primeira fase, a investigação, será efetuada através da recolha de todos os dados históricos e métodos disponíveis. As fontes para esta investigação serão a literatura, a documentação interna (manuais e procedimentos), documentação existente na indústria, artigos científicos e outras dissertações e teses. As informações recolhidas devem ser validadas, assegurando que diferentes fontes têm a mesma definição para vários métodos.

Uma vez concluída a primeira fase, a segunda fase basear-se-á em inquéritos aos diferentes departamentos que compõem a Hi Fly para recolher a opinião relativamente às vantagens, desvantagens e o que pode ser melhorado no atual método de avaliação do risco utilizado pela companhia aérea (Método BowTie).

Com base neste inquérito, será definida uma série de critérios que o processo de gestão e análise do risco deve cumprir e verificar quais os métodos que podem ser implementados. De seguida, será feita uma caraterização das vantagens e desvantagens destes métodos e, com base nos objetivos acima descritos, será utilizada a técnica MCDA mais concretamente a metodologia de medir a atratividade por uma técnica de avaliação baseada em categorias (M-MACBETH) para decidir qual o método que exponencia o lucro e a segurança das operações realizadas pela Hi Fly.

Finalmente, a terceira fase deste estudo consiste na verificação e discussão dos resultados obtidos e das principais contrariedades e limitações.

Análises e Resultados

A partir da análise dos inquéritos efetuados ao departamento de Safety, aos vários departamentos e dos resultados obtidos no programa M-MACBETH podemos concluir os seguintes pontos:

- A área mais valorizada num método de avaliação de riscos por cada departamento é a "capacidade de identificar o risco". Os resultados do inquérito do departamento de Safety confirmam que a "capacidade de identificar o risco" é a área mais relevante no processo de avaliação de riscos para a organização.
- A área menos relevante tem resultados diferentes quando se comparam os dois inquéritos. O departamento de Safety considera a área "suporte e atualizações" a menos relevante, enquanto os outros departamentos surpreendentemente consideram a área "facilidade de utilização" a menos importante.
- O indicador mais valorizado no método de análise BowTie é como este cumpre os regulamentos e legislação (“normas”).
- O indicador menos valorizado no método de análise BowTie é a facilidade de utilização e de atualizações frequentes.
- O método que obteve maior classificação segundo a metodologia M-MACBETH foi o método de análise de risco Esquema de Classificação de Risco Europeu (ERCS).

Estes pontos garantem que todos os objetivos propostos são cumpridos e fornecem à organização uma possível direção para a implementação de um novo método de avaliação dos riscos ou os pontos que podem ser melhorados no método utilizado atualmente.

Conclusões

Os resultados semelhantes de ambos os inquéritos demonstram a cultura de segurança da organização. Esta semelhança reflete que a segurança é a prioridade número um em todos os departamentos.

A justificação para a área “capacidade de identificar o risco” ser a mais valorizada advém do objetivo principal de uma avaliação de riscos. Uma avaliação do risco tem por objetivo avaliar o risco presente na operação e criar barreiras para mitigar ou eliminar esse risco, pelo que a área da "capacidade de identificar o risco" será a mais valorizada.

É possível concluir que a área "suporte e atualizações" é, em geral, o menos importante na organização, porque, para o departamento de Safety, é claramente o menos valioso, com uma pontuação muito baixa quando comparado com as outras áreas de análise, enquanto para os outros departamentos, mesmo que a área de "facilidade de utilização" seja o menos relevante, aparece apenas a dois pontos percentuais da área "suporte e atualizações".

Com as informações recolhidas nos inquéritos e no programa M-MACBETH, o método ERCS apresenta a melhor pontuação global, o que o torna o método mais adequado para as operações da Hi Fly. O método ERCS destaca-se pelo facto de ser o método mais completo no setor da aviação. A metodologia aborda o risco de uma ocorrência e não o seu resultado efetivo. Fornece a identificação das principais áreas de risco, uma abordagem harmonizada para a gravidade da ocorrência e uma determinação da probabilidade baseada na eficácia das barreiras que impediram o escalar da gravidade e das restantes barreiras.

Trabalhos Futuros

Durante a realização desta dissertação, foram encontradas algumas limitações, especialmente na criação de áreas-chave e indicadores-chave que permitissem o correto julgamento de um método de avaliação de riscos uma vez que, ainda não existe nenhum modelo que defina estas áreas e indicadores no setor da aviação. Também se provou uma limitação, a dificuldade em obter respostas ponderadas nos questionários devido à natureza do trabalho diário na empresa e a altura de realização do questionário durante os meses de Verão, que muitas vezes coincidem com os períodos de férias. Assim, as perspetivas para o trabalho futuro são as seguintes:

- Alargar os questionários: para incluir mais pessoas de vários departamentos, a fim de verificar se existem diferenças nos resultados.
- Melhoria contínua: Os métodos de avaliação de risco são um elemento importante do SMS e, com o surgimento de novos riscos devido ao elevado número de operações, as avaliações de risco devem esforçar-se por prever e mitigar possíveis riscos e perigos.
- Consideração dos fatores humanos: Investigar o impacto dos fatores humanos na eficácia do método de avaliação de riscos selecionado, abordando potenciais desafios e oferecendo estratégias de mitigação.
- Implementação: Implementar e validar o método de avaliação do risco selecionado nas operações da organização para avaliar a sua eficácia e adaptabilidade em cenários do mundo real.

Abstract

This dissertation arises due to the constant growth of the aviation industry and increased exposure to hazards and risks. This increase causes the growing need to create, implement and improve risk management systems by air operators, airports, and maintenance organisations to ensure the safety of operations, passengers, crews, and staff.

This dissertation focuses on choosing a risk analysis method most suitable for Hi Fly. The method must comply with all legislation in force and standards imposed by Hi Fly. To this end, a literature review of risk analysis methods suitable for aviation was carried out. This analysis begins by describing the risk management system proposed by the International Civil Aviation Organisation.

Then, each risk analysis method's process, structure, and objectives are described; a multi-criteria decision analysis is used, specifically the MACBETH methodology (Measuring attractiveness by a categorical-based evaluation technique) To choose the most suitable method for Hi Fly's operations. The first phase of the application of this technique consists of the creation of key performance areas and performance indicators. From these, the second phase consists of creating a survey for the Safety Links in each department and the members who make up the Safety department, where the questions are adapted so that the answer offers a rating scale. It is asked to rank each key performance area by its relevance and to answer each question on a scale of one to five. As the Safety department is more familiar with the existing risk analysis methods, another survey is made to compare each method for each indicator. The last phase involves assigning weights to the key performance areas according to their average relevance. The evaluation is done through the M-MACBETH software tool, designed to perform the MACBETH methodology. This evaluation provides the most suitable method for Hi Fly's operations.

The survey results of the various departments show that the most relevant area in a risk analysis is the ability to predict the impact and severity of the event and the creation of mitigating barriers and controls. The survey of the Safety department confirmed the result described above. As for the indicators, the results differ, but both agree that the least relevant indicator is the frequency and quality of the updates that the methods receive. This data defines the weights entered in the software and, together with the judgement made between the indicators for each method by the two specialists in the

Safety department, satisfies the criteria necessary for using the decision support software.

Using the data entered, the tool dictated that the risk analysis method best suited to Hi Fly's operations is the European Risk Classification System (ERCS).

Keywords

Risk Assessment; Multi-criteria Decision Analysis; BowTie Methodology; Aircraft Operator; Safety; Safety Management System.

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List of Acronyms

AAA	Anti-Aircraft Artillery
AI	Artificial Intelligence
ALARP	As Low as Reasonable Possible
AM	Accountable Manager
ANAC	Autoridade Nacional de Aviação Civil
AOC	Air Operator Certificate
ARMS	Aviation Risk Management Solutions
ATO	Approved Training Organisations
ATS	Air Traffic Service
CAMO	Continuing Airworthiness Management Organisation
CMM	Compliance Monitoring Manager
CVR	Cockpit Voice Recorder
EASA	European Union Aviation Safety Agency
ERC	Event Risk Classification
ERCS	European Risk Classification Scheme
ERP	Emergency Response Plan
FDM	Flight Data Monitoring
FDR	Flight Data Recorder
FMEA	Failure Mode and Effect Analysis
FTA	Fault Tree Analysis
HAZOP	Hazard and Operability Study
IATA	International Air Transport Association
ICAO	International Civil Aviation Organisation
ICBM	Intercontinental Ballistic Missile

IOSA	IATA Operational Safety Audit
KPA	Key Performance Area
KPI	Key Performance Indicator
MACBETH	Measuring Attractiveness through a Category-Based Evaluation Technique
MANPADS	Man Portable Air Defense Systems
MCDA	Multi-Criteria Decision Analysis
NP	Nominated Person
RPN	Risk Priority Number
SA	Safety Assurance
SAG	Safety Action Group
SAM	Surface to Air Missile
SDPM	Safety Department Procedures Manual
SIRA	Safety Issue Risk Assessment
SM	Safety Manager
SMM	Safety Management Manual
SMS	Safety Management System
SPI	Safety Performance Indicators
SPT	Safety Performance Targets
SRB	Safety Review Board
SRM	Safety Risk Management
SSP	State Safety Program
TM-CAD	Transport Malta Aviation Directorate
UK CAA	United Kingdom Civil Aviation Authority
UOS	Undesirable Operational State

1. Chapter 1 – Introduction

1.1. Motivation

The aviation industry is constantly growing. According to ICAO (International Civil Aviation Organisation), by the mid-2030s, no fewer than 200,000 daily commercial flights are expected to take off and land worldwide [1], almost twice as many as today. With more flights, the exposure to hazards and risks increases, which can lead to an increase in the number of accidents/incidents, hence the need to ensure the safety of all operations, passengers, crew, and staff.

Highlighting the importance of managing this exposure, in 2015, chairman Calin Rovinescu of IATA (International Air Transport Association) said that safety is the number one priority in aviation [2]. Safety is, according to ICAO, "The state in which risks associated with aviation, activities, related to, or in direct support of the operation of aircraft, are reduced and controlled to an acceptable level" [3:7]. Risk management processes are implemented in the aeronautical industry to mitigate the risk that arises from the various hazards associated with flying, starting from aircraft manufacturers, airports, service providers, and aircraft operators. In 2006, ICAO required most commercial aviation operators to implement an SMS (Safety Management System)[4]. The ICAO SMS framework consists of four components and twelve elements, and its implementation shall be commensurate with the size of the organisation and the complexity of the services provided [5].

The four main pillars of an SMS are safety policy and objectives, safety risk management (SRM), safety assurance, and safety promotion. Risk assessment is the main element within the SRM and is used for assessing the hazards, risk severity, and likelihood. It is critical to guarantee aviation safety because it involves many potential hazards that could result in serious accidents or incidents. By conducting a thorough risk assessment, aviation professionals can identify and mitigate risks before they become unsafe, increasing safety in every flight.

1.2. Object and Objectives

The object of this dissertation is the SRM of the SMS of an airline.

The main objective of this master's thesis is to conduct a study on which risk assessment method is most suitable for the airline's needs. The method needs to have the necessary guidelines from the Safety department and compliance to guarantee that it meets the airline's safety standards and regulations [3]. After this study, the selected risk assessment method will bring advantages to Hi Fly's SRM. The secondary objective is that it can be used as a guideline/framework for possible future works, thesis, and presentations for aviation organisations to define a risk assessment method suitable for their operations.

Hi Fly uses the BowTie methodology to identify the hazards, assess the risk, and evaluate the preventive and recovery controls (risk mitigation) [6]. Since Hi Fly's operations occur worldwide, the method must adapt to the various hazards and risks of the different missions.

The risk assessment method should use qualitative methods to identify potential risks and quantitative methods to evaluate the likelihood and potential impact of identified risks.

To decide which risk assessment methods are best suited for the airline´s needs, the Multi-Criteria Decision Analysis (MCDA) will be used, which is a systematic approach used to evaluate and rank different options based on a set of criteria that involves the use of mathematical and statistical techniques to identify and evaluate multiple criteria to make an informed decision [7].

With this, Hi Fly will better assess the risks (operational or technical) involved in its operations. Subsequently, it will make the airline's operations more rentable and safer.

1.3. Methodology

The development of this study is divided into three phases.

Phase one, research, will be done by gathering all historical data and available methods. The sources for this research will be literature, in-house documentation, industry documentation, scientific articles, and other dissertations and thesis. The information gathered must be validated, ensuring that different sources have the same definition for several methods.

Once the first phase is concluded, phase two will be based on surveys to the various departments that are part of the airline to gather their opinion regarding the advantages, disadvantages, and what can be improved in the current method for risk assessment (BowTie Method) used by the airline.

Based on this inquiry, a series of criteria will be defined that the risk assessment must meet and verify which methods can be implemented. Next, a characterisation of the advantages and disadvantages of these methods will be made, and based on the objectives described above, the MCDA technique will be used to decide the method that exponentiates the profit and safety of the operations carried out by the airline.

Finally, the third phase of this study is verifying and discussing the results obtained and the main setbacks and limitations. Figure 1 provides a summary of the methodology used in this dissertation.

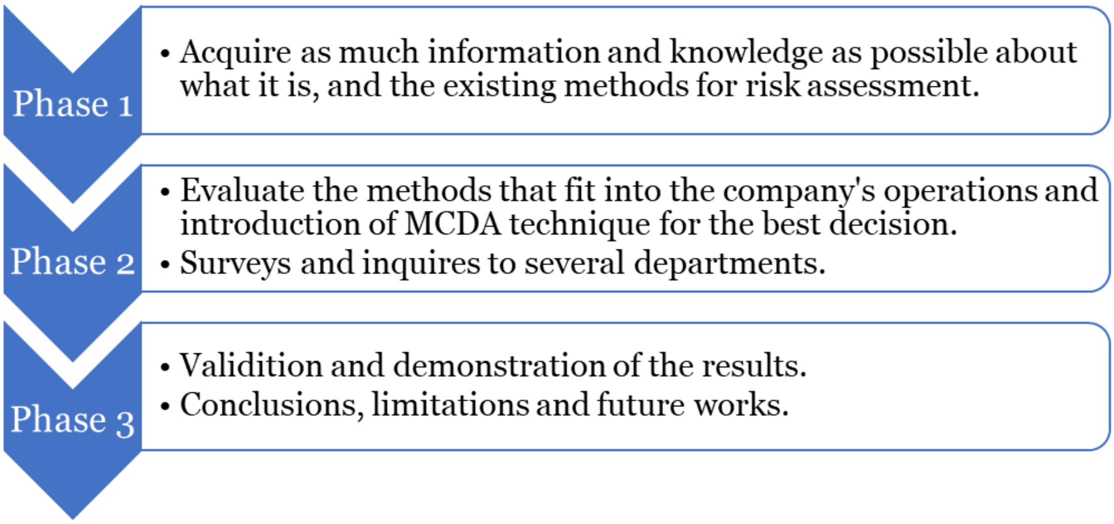

Figure 1 - Methodology used in this dissertation (Own elaboration).

1.4. Dissertation Structure

The structure of this dissertation is divided into five chapters: introduction, state of the art, Hi Fly, case study, and conclusions.

The first chapter is the introduction, where a small summary is made about the safety concept, the SMS concept, and how these concepts evolved to what they are today (Motivation). It describes the object, objectives, methodological steps, and the dissertation structure that will be followed.

In chapter two, a state-of-the-art review is described. It explains what SMS is and the four pillars that every SMS sits on, with a special focus on hazard identification, risk assessment, and risk mitigation [8]. Chapter 2 ends with a description of risk assessment methods used by the industry and other tools for risk assessments that can be suitable for airlines [9].

In the third chapter, Hi Fly's departmental organisation and the current SMS and risk assessment method are described.

The case study is presented in chapter four. The MCDA decision method and the MACBETH (Measuring Attractiveness by a Categorical Based Evaluation Technique) technique and software are described. It explains the methodology inherent to the surveys by creating a set of KPAs (Key Performance Areas) and KPIs (Key Performance Indicators). It presents and describes the weights and scores allocated to each question in the inquiry. Chapter four concludes with the results. The results are discussed, and some conclusions are drawn.

The fifth chapter presents the conclusions from the dissertation. A synthesis of the dissertation is made and it is discussed some remarks, limitations and final considerations about the work done. Finally, suggestions for further development of the risk assessment process are presented for an ever-evolving aviation industry.

1.5. Definitions

Accountable Manager - is responsible for operations and the overall implementation and maintenance of the organisation's Safety Management System. (ICAO)

ACMI contract - the wet-lease agreement between operators, which includes aircraft, technical, and cabin crew exclusively from the lessor, maintenance, and insurance. (ANAC)

Chicago Convention - the Convention on International Civil Aviation, signed in Chicago on 7 December 1944, approved for ratification by Decree-Law No 36 158 of 17 February 1947, and ratified by letter of ratification of 28 April 1948. (ANAC)

Damp lease contract - wet lease contract between operators, including only the lessor's technical crew and the lessee's cabin crew. (ANAC)

A dry lease-in contract – is an agreement between two air carriers in which an aircraft (without crew) is operated under the certificate (AOC) of the lessee. The aircraft is included in the national operator's AOC in this case.

Dry lease-out contract - an agreement between two air carriers in which an aircraft (without crew) is operated under the certificate (AOC) of the lessee. In this case, the aircraft is excluded from the national operator's AOC and included in the lessee's AOC. (ANAC)

Hazard - A condition, object, activity, or event with the potential to cause human harm, damage to equipment or structures, material losses, or reduced ability to perform a function. (ICAO)

Likelihood - is the probability or frequency that a hazard can occur. (ICAO)

Management - includes defining goals, measuring performance, comparing performance targets vs. indicators, and taking corrective action when necessary. (ICAO)

Risk - The likelihood of injury to personnel, damage to equipment or structures, loss of material, or reduced ability to perform a prescribed function, measured in probability and severity. (ICAO)

Safety - is the state in which risks associated with aviation activities, related to or in direct support of the operation of aircraft, are reduced and controlled to an acceptable level. (ICAO)

Safety Issues - Manifestation of a hazard or a combination of several hazards in a specific context. (Hi Fly)

Safety Management System - is a systematic approach to managing safety, including the necessary organisational structures, accountability, responsibilities, policies, and procedures. (ICAO)

Severity - The consequence or impact of a hazard regarding the degree of loss or harm. (ICAO)

System - is an organized, purposeful structure that consists of interrelated and interdependent elements and components and related policies, procedures, and practices created to carry out a specific activity or solve a problem. (ICAO)

Threat - existent condition in a certain environment or procedure possible to become a hazard. (ICAO)

Uncertainty - lack of sureness about someone or something

Wet lease-in contract - is an agreement between two air carriers in which an aircraft (with crew) is operated under the lessor's certificate (AOC). In this case, the aircraft is not included in the national operator's AOC. (ANAC)

Wet lease-out contract - is an agreement between two air carriers in which an aircraft (with crew) is operated under the lessor's certificate (AOC). In this case, the aircraft remains on the national operator's AOC, but the commercial responsibility for its operation lies with the lessee. (ANAC)

2. Chapter 2 – Literature Review

2.1. Introduction

The aviation sector has witnessed an unprecedented surge in passenger growth, with IATA estimating that approximately five billion passengers are set to take the skies by the end of 2023. As passenger numbers continue to increase, presenting opportunities and challenges, air operators face significant financial and operational strain because of the aviation system's complexity, fast-shifting operational environment, and onerous authority regulations. A systematic approach to safety management is required to ensure the operator complies with those criteria and maintains profitability.

According to ICAO [10], progress in aviation safety can be described by four approaches, which roughly align with eras of activity. The approaches are listed below and are illustrated in Figure 2.

a) Technical - Aviation became a popular means of mass transportation from the early 1900s until the late 1960s. During this time, safety concerns in the aviation industry were primarily attributed to technical factors and technological failures, and efforts were focused on identifying and addressing these issues. Technological advancements decreased the rate of accidents, and safety measures were expanded to include regulatory compliance and oversight.

b) Human factors - By the early 1970s, aviation had become significantly safer due to significant technological advancements and improvements in safety regulations. The focus of safety measures, particularly the relationship between humans and machines, expanded to include the human element. However, despite efforts to mitigate errors, human factors continued to play a role in accidents. Early human factors analysis focused solely on the individual without fully considering the broader operational and organisational context. It wasn't until the early 1990s that experts began to recognise the complex environment in which individuals operate, considering multiple factors that could impact behaviour.

c) Organisational - In the mid-1990s, the concept of safety evolved from a narrow focus on technical and human factors to a more comprehensive and systemic approach that included organisational factors. This new perspective introduced the idea of "organisational accidents," which recognised the influence of culture and policies on safety risk controls. Furthermore, adopting reactive and proactive safety data collection and analysis methods allowed organisations to monitor known risks and identify emerging trends. These improvements provided the groundwork for the current safety management approach.

d) Total system - Since the start of the 21st century, many states and service providers have embraced the safety approaches of the past and advanced to a higher level of safety maturity. Moreover, this has involved implementing SMSs or State Safety Programs (SSPs), resulting in improved safety outcomes. However, safety systems have mainly focused on individual safety performance and local control without fully considering the broader context of the entire aviation system. Therefore, this has led to increased recognition of the aviation system's complexity and various organisations' involvement in aviation safety. There have been many accidents and incidents where the interfaces between organisations have contributed to negative outcomes, highlighting the need for a more holistic approach to aviation safety. So, to solve this problem, in 2013, ICAO introduced the first edition of Annex 19, which will be described in the next chapter.

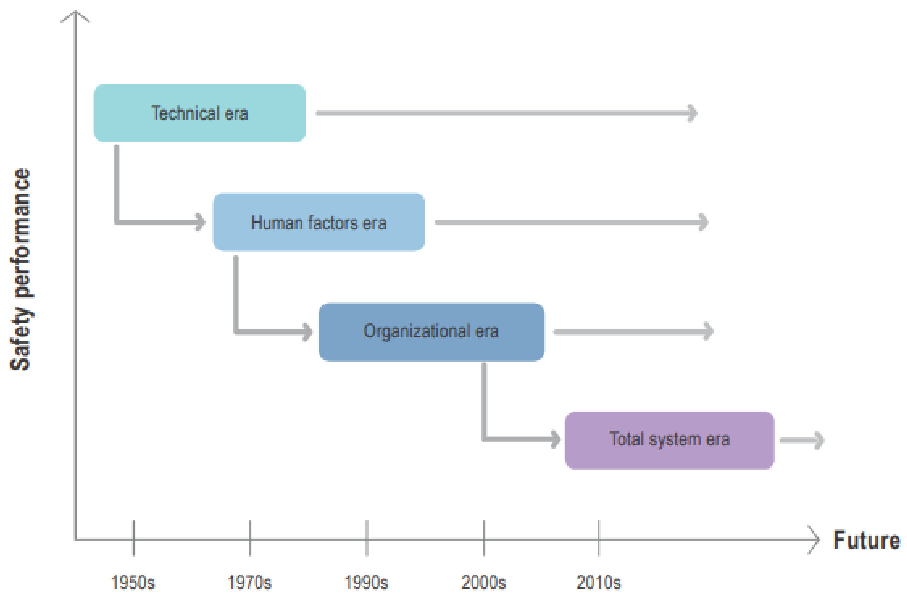

Figure 2 – The evolution of safety [10].

2.2. Safety Management System (SMS)

As the world today lives in a “total system” era regarding safety, it is crucial to examine the factors contributing to incidents and potential accidents thoroughly. This analysis helps enhance the understanding of such events and take necessary steps to prevent them. To achieve this, operators must establish, implement, and maintain a well-structured management system that incorporates their organisation's necessary standards and requirements. According to [10], a system is an organized, purposeful structure comprising interrelated and interdependent elements, components, and related policies, procedures, and practices created to carry out a specific activity or solve a problem. In November of 2013, based on this definition, ICAO made applicable Annex 19, where a framework guidance for SMS was introduced.

According to ICAO, an SMS is a systematic approach to managing safety, including the necessary organisational structures, accountability, responsibilities, policies, and procedures.

A well-implemented SMS has the goal of giving a systematic approach to managing safety, continuously enhancing safety performance by identifying hazards and threats, ensuring that remedial action necessary to maintain an acceptable level of safety is implemented, providing for continuous monitoring and regular assessment of the safety level achieved, and aim to make continuous improvements to the overall level of safety.

Creating an SMS involves combining management processes and activities into one system. However, designing safety management activities systematically and scientifically requires applying certain techniques, approaches, and models. These techniques and models help identify and analyse risks, establish safety goals, design safety measures, and implement mitigation actions.

Implementing an SMS requires processes that allow the control of safety risks and introduce the concept of an acceptable level of safety. The implementation of an SMS should sit on four main pillars:

Pillar 1 - Safety Policy and Objectives

An effective SMS requires policies and procedures that clearly define roles, responsibilities, and relationships among all stakeholders in maintaining safe operations. Safety must be a core value of the organisation and integrated into its mission and vision.

The SMS must use quality management principles but objectively assess safety risks rather than only customer satisfaction or monetary gains. Each interface between production, operation, and oversight must be identified, and each subsystem must be designed to provide the organisation with everything it needs to perform its role.

Executive management must be personally involved in safety activities, and SMS policy documentation must reflect this requirement. Key behaviours that demonstrate executive management involvement include including safety goals in strategic plans and regular management reviews of the SMS.

Operational departments must have clear requirements for documenting procedures, controls, training, process measurements, and change management. The SMS must be designed to ensure that all stakeholders are accountable and expectations are clearly defined.

Pillar 2 - Safety Risk Management

SRM is a key component of an SMS designed to identify, assess, and manage safety risks associated with an organisation's operations. The goal of SRM is to proactively identify potential hazards, assess the likelihood and severity of those hazards, and then implement risk controls to mitigate or eliminate the risks [10], [11].

During hazard identification, potential hazards are identified through various methods, such as safety audits, incident investigations, safety reports, and overall industry inputs. Once hazards are identified, they are assessed to determine their likelihood and severity [11].

Every operation involves some risk degree, so it is important to adopt a proper risk management approach, including developing procedures for accepting risks. Moreover, this involves setting acceptance criteria and clearly defining the authority and responsibility of decision-makers in managing risks [11].

Risk control/mitigation involves implementing risk controls to mitigate or eliminate the identified risks. Moreover, this can include implementing engineering controls, administrative controls, or personal protective equipment, depending on the hazard's nature and the risk level [10].

Pillar 3 - Safety Assurance

It consists of processes and activities to determine whether the SMS operates according to expectations and requirements. Therefore, this involves continuously monitoring its processes and operating environment to detect changes or deviations that may introduce emerging safety risks or the degradation of existing safety risk controls. Such changes or deviations may then be addressed through the SRM process. Safety Assurance (SA) activities should include developing and implementing actions taken in response to any identified issues with a potential safety impact. These actions continuously improve the performance of the SMS [10].

SA is then monitored through the ongoing evaluation and analysis of safety-related data and information. This data can come from a variety of sources, such as the SRM itself, safety audits (external and internal), and SPIs (Safety Performance Indicators) [11].

Pillar 4 - Safety Promotion

Safety Promotion is designed to create a safety culture within an organisation. It involves activities and strategies to raise awareness and promote safety at all levels of the organisation, from top management to frontline employees [8].

Implementing strict policies and procedures alone is insufficient to ensure effective safety management. A successful safety management system should also focus on promoting a positive safety culture that influences the behaviour of both individuals and the organisation.

Through training, communication, and incentives, a Safety Culture is built where safety is a core value and promoting positive behaviour that supports safe work practices, organisations can reduce the risk of incidents and create a safer work environment for employees [10].

A positive Safety Culture encourages an SMS that should primarily be proactive or preferably strive to be predictive. It needs to consider hazards and risks that impact the whole organisation and risk controls to minimize risk exposure.

2.2.1. Risk Management

ICAO defines Risk Management as the identification, analysis, and elimination (and/or mitigation to an acceptable or tolerable level) of those hazards and the subsequent risks that threaten the viability of an organisation [3].

Risk Management aims to ensure that the risks associated with hazards to flight operations are systematically and formally identified, assessed, and managed within acceptable safety levels.

In aviation operations, it is impossible to eliminate all risks as it would require stopping all aviation activities, which is not practical or economically feasible. Therefore, it is generally accepted that there will always be some residual risk of harm to people, property, or the environment. However, this residual risk is considered acceptable or tolerable if appropriate risk management measures are in place to minimize it to an acceptable level. The responsible authority and society acknowledge that a certain level of risk is inherent in aviation operations. Still, they expect that aviation stakeholders take appropriate measures to manage the risks and ensure the safety of everyone involved.

Risk management, a central component of the SMS, plays a vital role in addressing the risk practically. It requires a coherent and consistent objective analysis process to evaluate the operational risks. Risk Management is generally a structured approach and systematic actions to balance the identified and assessed risk and practicable risk mitigation [12]. In the process of Risk Management, there are three steps considered essential [8]:

1. **Hazard identification**- Identifying undesired or adverse events that can lead to a hazard and analysing mechanisms by which these events may occur and cause harm. The methods and techniques for hazard identification are described further down.
2. **Risk assessment**- After identifying potential hazards, assessing their criticality and ranking them based on their potential risk is essential. Moreover, this involves evaluating the severity of their potential consequences and the likelihood of their occurrence. This assessment can be conducted by experienced personnel or using formal techniques and analytical expertise. If the assessment indicates the risk is within acceptable limits, the operation can continue without intervention. However, risk mitigation processes are initiated if the risk is deemed unacceptable.
3. **Risk mitigation** involves developing and implementing measures to reduce the likelihood of the hazard occurring or minimize its potential consequences. Therefore, this may involve implementing new procedures, modifying existing equipment or processes, providing additional training, or introducing new technology. The success of the risk mitigation process is then evaluated to determine whether it has effectively reduced the level of risk to an acceptable level. The process may involve ongoing monitoring and review to ensure the implemented measures effectively mitigate the risk.

Figure 3 depicts the risk management process according to ICAO.

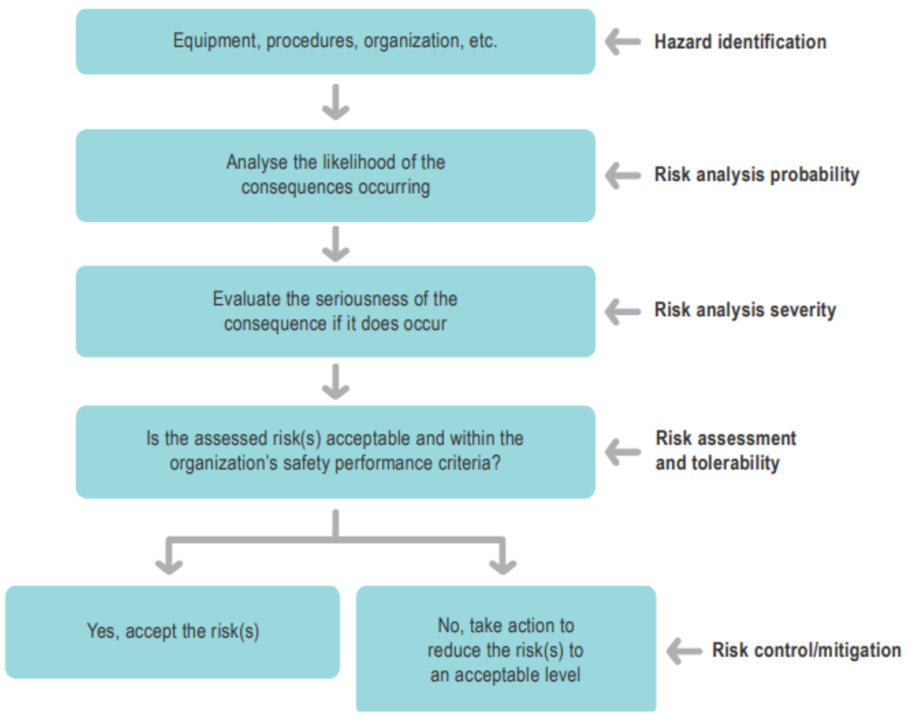

Figure 3 – ICAO Risk Management Process [10].

2.2.2. Hazard Identification Approaches

The first step in Risk Management is identifying hazards that could risk aviation safety. Therefore, this can be done through various methods, including incident and accident reporting, safety audits, and data analysis. Once the hazards have been identified, they should be documented and prioritized based on their severity and likelihood of occurrence.

ICAO emphasizes that three different approaches should be considered when identifying potential hazards in aviation. In other words, these three methods are crucial in the hazard identification process [10]:

Reactive - method involves identifying hazards by investigating past incidents or accidents. Analysing past incidents' causes and contributing factors can identify hazards affecting procedures, and corrective actions can be taken to prevent similar incidents.

The proactive - method involves identifying hazards while performing operational tasks or activities and responding promptly to avoid potential negative outcomes. This approach requires experience and the ability to respond to situations quickly. The safety information for proactive hazard identification primarily comes from FDM programs, safety reporting systems, and the safety assurance pilar.

Predictive - method involves analysing procedures and preparing new activities by using reference data or studies to anticipate potential negative outcomes that could occur in the future. Moreover, this allows for the development of defences to prevent or mitigate these outcomes and helps improve overall safety standards.

2.2.3. Risk Assessment

According to ICAO, risk assessment is "a systematic process to evaluate all identified hazards, assess the risk(s) they pose, and determine the adequacy of any existing or planned controls". The goal is to determine the degree of safety associated with a particular action or operation by identifying the anticipated risk(s) and offering guidance in the decision-making roles to accept or deny the risk(s) to which the operation is projected to be exposed. Through this assessment, based on a predetermined acceptable level of risk, mitigation techniques and corrective actions can and should be implemented under the safety hazards, trying to lessen their potential impact. The elements that make up a risk assessment are described in the next sub-chapter.

2.2.3.1. Risk Classification

Risk classification is a process of categorizing risks based on their potential severity and probability of occurrence. It is an important step in risk management as it helps organisations prioritize their efforts and resources toward managing the most critical risks.

Risks are described as a measure of the expected losses that an undesired event can cause, factored with the probability of the event occurring; that is, risk equals severity x likelihood [8].

Once a hazard has been assessed for its severity and likelihood, it is classified based on the descriptive level and corresponding quantitative index for each factor.

2.2.3.1.1. Probability

The probability represents the likelihood of a certain undesired state arising from the identified hazard.

A hazard is considered foreseeable if any reasonable person could have expected the occurrence to happen under the same circumstances. Identification of every conceivable or theoretically possible hazard is not possible. Therefore, good judgment is required to determine an appropriate level of detail in hazard identification.

Table 1 is an example of a safety risk probability table that categorises the likelihood of a safety risk occurring based on quantitative terms. The table presents five categories, each with a description and a corresponding numerical value. This table aims to provide a general overview of the likelihood of safety risks and to aid in prioritising safety measures. However, it should be noted that a more precise assessment of safety risk probability can be achieved with quantitative terms, providing a more accurate and objective risk assessment [10], [11].

Table 1 - Safety Risk probability table. Source: adapted from [10].

Likelihood	Meaning	Value
Frequent	Likely to occur many times (has occurred frequently)	5
Occasional	Likely to occur sometimes (has occurred infrequently)	4
Remote	Unlikely to occur, but possible (has occurred rarely)	3
Improbable	Very unlikely to occur (not known to have occurred)	2
Extremely Improbable	Almost inconceivable that the event will occur	1

2.2.3.1.2. Severity

Safety risk severity refers to the degree of harm or damage resulting from an unsafe condition, event, or activity.

The severity classification should consider [10]:

a) fatalities or serious injury which would occur as a result of:

1) being in the aircraft.

2) having direct contact with any part of the aircraft, including parts that have become detached from the aircraft.

3) having direct exposure to jet blast.

b) damage:

1) damage or structural failure sustained by the aircraft which:

i) adversely affect the aircraft's structural strength, performance, or flight characteristics.

ii) would normally require major repair or replacement of the affected component.

2) damage sustained by air traffic service (ATS) or aerodrome equipment which:

i) adversely affect the management of aircraft separation.

ii) adversely affects landing capability.

Table 2 is an example of a safety risk severity table typically used to categorize safety risks based on their potential impact. It includes five different categories that represent varying degrees of severity, and each category is described with a brief explanation of the level of harm or damage that may result. Additionally, each category is assigned a value to help prioritize risks based on severity.

Table 2 - Safety Risk severity table. Source: Adapted from [10]

Severity	Meaning	Value
Catastrophic	• Aircraft / equipment destroyed • Multiple deaths	A
Hazardous	• A large reduction in safety margins, physical distress or a workload such that operational personnel cannot be relied upon to perform their tasks accurately or completely • Serious injury • Major equipment damage	B
Major	• A significant reduction in safety margins, a reduction in the ability of operational personnel to cope with adverse operating conditions as a result of an increase in workload or as a result of conditions impairing their efficiency • Serious incident • Injury to persons	C
Minor	• Nuisance • Operating limitations • Use of emergency procedures • Minor incident	D
Negligible	• Few consequences	E

2.2.3.1.3. *Risk Assessment Matrix*

A risk matrix is a visual tool that maps the probability of an event occurring against its potential impact. The resulting matrix is divided into risk zones, each with a corresponding risk severity level.

The severity is given a level and index from A to E, while the likelihood is given a level and index from 1 to 5. These classifications combine the two indexes, which are then analysed using a safety risk matrix in Table 3.

The safety risk assessment matrix index should then be exported to a safety risk tolerability table. Safety risk tolerability refers to the acceptable level of risk an individual or organisation is willing to tolerate to achieve specific goals or objectives.

Table 3 - Safety Risk Matrix. Source: Adapted from [10].

Safety Risk	Severity				
Probability	Catastrophic A	Hazardous B	Major C	Minor D	Negligible E
Frequent 5	5A	5B	5C	5D	5E
Occasional 4	4A	4B	4C	4D	4E
Remote 3	3A	3B	3C	3D	3E
Improbable 2	2A	2B	2C	2D	2E
Extremely Improbable 1	1A	1B	1C	1D	1E

The safety risk tolerability table helps the individual or organisation take the necessary actions to mitigate the risk. Following Table 4, if safety risks are assessed and initially fall into the intolerable region, they are deemed unacceptable under any circumstance. Therefore, this implies that the likelihood and/or seriousness of the consequences associated with the risks is high, and the potential damage they can cause poses a significant threat to safety. As a result, immediate action must be taken to mitigate the identified hazards or stop the activities altogether. But, if a safety risk is considered intolerable, it requires urgent intervention to prevent harm or damage to people or property.

Table 4 – Safety Risk Tolerability. Source: Adapted from [10].

Safety risk Index Range	Safety risk description	Recommended action
5A, 5B, 5C, 4A, 4B, 3A	Intolerable	Take immediate action to mitigate the risk or stop the activity. Perform priority safety risk mitigation to ensure additional or enhanced preventative controls are in place to bring down the safety risk index to tolerable.
5D, 5E, 4C, 4D, 4E, 3B, 3C, 3D, 2A, 2B, 2C, 1A	Tolerable	Can be tolerated based on the safety risk mitigation. It may require management decision to accept the risk.
3E, 2D, 2E, 1B, 1C, 1D, 1E	Acceptable	Acceptable as is. No further safety risk mitigation required.

2.2.4. Risk Mitigation

According to ICAO, the definition of risk mitigation is the process of lowering the risk to a level that is as low as reasonably practical [10]. To effectively manage risks, it is necessary to identify and categorize them to develop and implement appropriate mitigation measures.

Generally, according to ICAO, safety risk mitigation strategies fall into three categories:

1. **Avoidance:** The operation or activity is cancelled or avoided because the safety risk exceeds the benefits of continuing the activity, thereby eliminating the safety risk.
2. **Reduction:** The frequency of the operation or activity is reduced, or action is taken to reduce the magnitude of the consequences of the safety risk.
3. **Segregation:** Action is taken to isolate the effects of the safety risk's consequences or build redundancy to protect against them.

This process enables air operators to determine acceptable risks based on company policies and procedures. Additionally, it ensures that any changes or new situations are evaluated regarding their safety impact and classified according to their severity. In determining appropriate risk mitigation measures, a cost-benefit analysis is often conducted to assess whether the measures are economically viable and whether the organisation should accept the risk or cancel the operation. In simpler terms, risk mitigation involves identifying and classifying risks, evaluating their safety impact, and determining whether the cost of mitigation is justified or whether alternative actions should be taken [11].

2.2.4.1. Safety Performance Monitoring and Measurement

According to [3], safety performance monitoring and measurement represent the means to verify the organisation's safety performance and to validate the effectiveness of safety risk controls (risk mitigation measures). The safety performance monitoring is evaluated through two measurements:

- Safety Performance Indicators (SPIs).
- Safety Performance Targets (SPTs).

A SPI is a data-based parameter that is a crucial tool for evaluating and monitoring safety performance. This assessment process involves benchmarking, reviewing, or risk assessment to effectively identify potential safety measures and gauge their efficacy [13]. SPIs can be classified as quantitative or qualitative.

Quantitative indicators can be expressed as a number or as a rate. A numerical expression will sometimes be sufficient; however, qualitative indicators are descriptive and measured by quality (work experience, professional judgment).

According to the three hazard identification approaches described in section 2.2.2, SPIs can be divided into leading or lagging indicators.

Leading indicators are focused on future safety performance and promoting continuous improvement. Their "leading" nature stems from the fact that they assess safety proactively, well before any actual operational events occur. By encompassing proactive and predictive processes, these indicators serve as valuable tools for enhancing safety. They enable the implementation of the mitigating measure in advance, effectively preventing harm and significantly reducing the likelihood of accidents. As a result, they play a pivotal role in substantially improving overall safety standards.

Leading indicators can be positive when used to monitor conditions that contribute to increased safety or negative when used to monitor conditions with the potential to contribute to a decrease in safety.

Lagging indicators measure events that have already occurred. It helps the organisation understand what has happened in the past and is useful for long-term trends. Because lagging SPIs measure safety outcomes, they can measure the effectiveness of safety mitigations. They are effective at validating the overall safety performance of the system. Since lagging indicators are associated with the surveillance of safety events that have already taken place, these indicators are associated with reactive processes.

Lagging SPIs are divided into two types [3:4-5,4-6]:

- **Low probability/high severity:** outcomes such as accidents or serious incidents. The low frequency of high-severity outcomes means that data aggregation (at the industry segment or regional level) may result in more meaningful analyses.
- **High probability/low severity:** outcomes that did not necessarily manifest themselves in a serious accident or incident; these are sometimes also referred to as precursor indicators. SPIs for high probability/low severity outcomes are primarily used to monitor specific safety issues and measure the effectiveness of existing safety risk mitigations.

Figure 4 depicts the classification, categories, and types of SPIs.

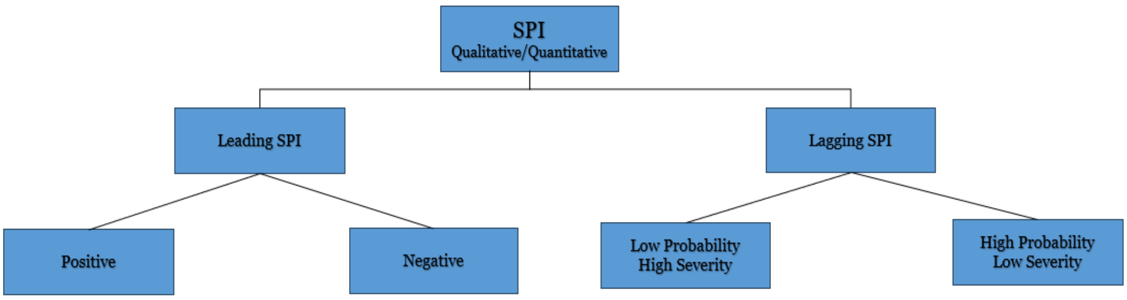

Figure 4 – Description of SPIs. Source: Own elaboration.

The Safety Performance Targets (SPT) are the planned or intended objectives for safety performance indicators over time. Targets should be time-bound and set to ensure the achievement of the acceptable level of safety desirable and realistic for the operator. The target could be presented either in absolute or relative terms. Typically, SPTs are expressed as a rate or number reduction, indicating its aim and the period to achieve it.

2.3. Risk Assessment Methods

Risk assessment methods are critical in ensuring aviation safety. The aviation industry has implemented various risk assessment methods to identify, analyse, and manage risks associated with flight operations. These methods enhance safety by identifying potential hazards and implementing control measures to mitigate risks.

Currently, there are various methods of conducting risk assessment, and the choice of method will depend on the nature and complexity of the risk, the specific needs and goals of the organisation, and the availability of data and resources.

Some of these methods are described below.

2.3.1. Aviation Risk Management Solutions (ARMS)

ARMS is a methodology for operational risk assessment applicable to aviation organisations and developed by the ARMS working group between 2007-2010 [14].

The ARMS methodology is used to develop risk management strategies and to ensure that aviation operations are conducted safely and efficiently. It involves using various risk assessment techniques, including hazard identification, risk analysis, and risk evaluation.

The goal is to reduce the likelihood of accidents and incidents in aviation operations. By identifying potential risks and developing appropriate risk management strategies, the methodology helps ensure that aviation operations are conducted safely and with minimal risk to passengers, crew, and the environment.

According to [15], current risk assessment methods tend to be applied universally to all three risk assessments described below and generally fail to differentiate between Safety Events, Safety Issues, and Safety Assessments.

Operational risk assessment is therefore needed in three different contexts:

1. Individual Safety Events may reflect a high-risk level and require urgent action. Therefore, all incoming events need to be risk-assessed. This step is called Event Risk Classification (ERC).

2. The Hazard Identification process may lead to identifying Safety Issues, which need to be risk assessed to determine what actions are needed. This step is called Safety Issue Risk Assessment (SIRA).

3. Occasionally, there will be a need to carry out Safety Assessments, typically related to a new or revised operational activity, for example, a new destination. The activity needs to be risk assessed at the planning stage, according to the "Management of Change" process of the company.

The process of the ARMS methodology is represented in Figure 5.

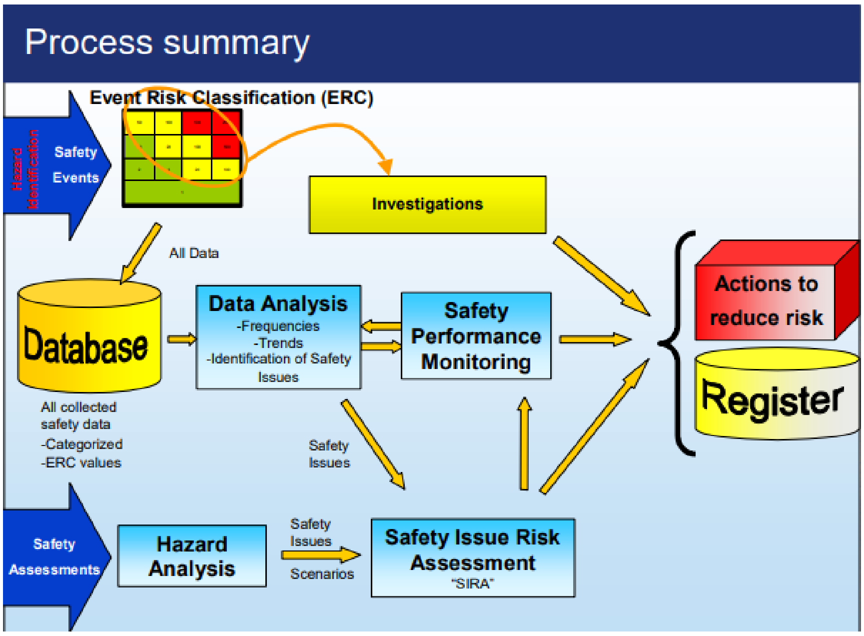

Figure 5 – The risk assessment process flowchart [15]

The main rule is that ERC is used for events (even when there is no actual consequence), and SIRA is used for issues (including hazards and latent conditions).

The assessment process starts with ERC, the first review of events regarding urgency and the need for further investigation. This step also attaches a risk value (ERC value) to each event – which is necessary for creating safety statistics reflecting risk.

The ERC value is based on two questions:

- Question 1 - What would have been the most credible accident outcome if this event had escalated into an accident?

- Question 2 - What was the effectiveness of the remaining barriers between this event and the most credible accident outcome?

The practical ERC application is represented through a 4x4 matrix (Table 5).

The first question specifies the most credible scenario, judges its typical consequence, and picks the corresponding row in the matrix. The listed "typical accident scenarios" are on the right of the matrix.

The second one determines the access to the remaining "safety margin", considering both the number and robustness of the remaining barriers between this event and the accident scenario in Question 1.

Overall, Question 1 defines the row of the matrix, and Question 2 defines the column.

Table 5 – ERC Matrix. Source: Adapted from [15].

Question 2 What was the effectiveness of the remaining barriers between this event and the most credible accident outcome?				Question 1 If this event had escalated into an accident, what would have been the most credible accident outcome?		Typical accident scenarios
Effective	Limited	Minimal	Not effective			
50	102	502	2500	Catastrophic Accident	Loss of aircraft or multiple fatalities (3 or more)	Loss of control, mid air collision, uncontrollable fire on board, explosions, total structural failure of the aircraft, collision with terrain.
10	21	101	500	Major Accident	1 or 2 fatalities, multiple serious injuries, major damage to the aircraft	High speed taxiway collision, major turbulence injuries.
2	4	20	100	Minor Injuries or Damage	Minor injuries, minor damage to aircraft	Pushback accident, minor weather damage.
1				No Accident Outcome	No potential damage or injury could occur	Any event which could not escalate into an accident, even if it may have operational consequences (e.g. diversion, delay, individual sickness).

The ERC has two outputs. The first output is a recommendation on what should be done about the event. The results should be interpreted as follows in Table 6.

Table 6 – Interpretation of the results. Source: Adapted from [15].

(red)	→	Investigate immediately and take action.
(yellow)	→	Investigate or carry out further Risk Assessment.
(green)	→	Use for continuous improvement (flows into the Database).

The second output of the ERC is a number called the ERC risk index. This index gives a quantitative relative risk value stored as data in a safety database, which is used for data analysis. Charts, graphs, and filters are produced that sort events by different combinations, such as time, aircraft type, airport/approach, event types, keywords, aircraft systems, and operational issues. Moreover, this may lead to actions due to increasing trends, sometimes without a formal risk assessment. So, this is key to identifying current Safety Issues. An ERC template is shown in Annex A.

Sometimes, the results will immediately highlight issues that need to be addressed – even before a formal risk assessment. Results can be presented as "number of events" or "rate of events".

Focusing solely on metrics like "several events" or "rate of events" to assess safety can be misleading since these do not consider the potential severity of the events. Therefore, shifting from a "number" focused approach to a "risk" one is important when making safety-related decisions. The ERC risk index values provide a useful way to achieve this. By using ERC values, organisations can better understand the likelihood and potential impact of events, which can guide decision-making in a more informed and accurate manner. Therefore, this applies to any assessment used to evaluate safety.

As a result of data analysis, the organisation will gradually identify several Safety Issues affecting its operation. These must be risk-assessed using the SIRA.

SIRA is the risk assessment of Safety Issues, which includes the risk controls (barriers) in the assessment.

The first step is to define and scope the Safety Issue properly.

Typical aspects to define are the safety issue title, description of hazard(s), description of related accident scenario(s), locations considered, the period under study, and departments whose involvement in the assessment is necessary. Defining correctly the Safety Issue makes the assessment more factual.

Once the Safety Issue has been defined, the analyst must create the applicable accident scenario(s). These scenarios can then be risk-assessed using SIRA. Typically, a scenario's highest risk becomes the Safety Issue risk value.

SIRA assesses the risk using a formula where risk has four factors instead of using the old "severity x likelihood" formula:

- Frequency/probability of the so-called Triggering Event.
- Effectiveness of the Avoidance Barriers.
- Effectiveness of the Recovery Barriers.
- The severity of the (most probable) accident outcome.

The triggering event may be from various origins (some examples are given in Figure 3). The first factor is an estimate of the exposure to this event. It may often be expressed as "X times / Y flights".

The second and third factors in the SIRA formula are estimates of the effectiveness of the avoidance and recovery barriers. Finally, the fourth factor is the severity of the accident outcome, in line with the ERC vertical scale.

The first step in the model is the Triggering Event, which is the initial event that sets off the chain of events leading to a potential accident. Avoidance Barriers are put in place to prevent the situation from escalating into an Undesirable Operational State (UOS), which could be dangerous, such as a collision, an aircraft upset, etc.

The UOS marks the point at which the situation has escalated beyond the control of the Avoidance Barriers, and Recovery Barriers come into play. Recovery Barriers are designed to mitigate the situation and prevent it from resulting in a severe accident.

According to [15], the frequency (or likelihood) is always the likelihood of the triggering event, and the severity is always the severity of the accident outcome.

The SIRA model is represented in Figure 6.

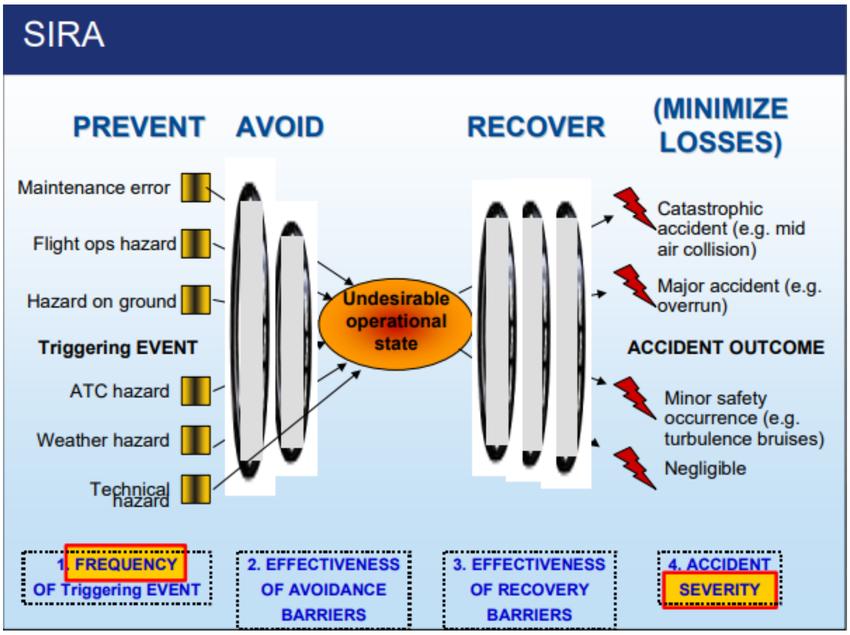

Figure 6 – The model behind SIRA [15]

2.3.2. European Risk Classification Scheme (ERCS)

The European Risk Classification Scheme (ERCS) is a tool the European aviation industry uses to assess the safety risk of aviation events and incidents. It was developed by EASA and is based on the ARMS methodology. The ERCS follows core principles of the ERC method as an event-based risk level assessment, a probability assessment based on the effectiveness of the stopping and remaining barriers, and a qualitative and quantitative safety risk score of an occurrence and not its actual outcome [16].

Compared to ERC, this model introduces the identification of the key risk areas (including a comparison of their risk levels) and a harmonized approach for event severity and probability determination.

The ERCS score consists of two values:

Firstly, the row score comprises the row letter (for example, M) and the column number (for example, 7). Such marking is specific to each box in the matrix and provides the ERCS score that would be, in this case, M7. Secondly, each box has an associated numerical equivalent score (see Table 11), which helps to support the analysis of aggregated risk-classified data.

According to [16], the ERCS process consists of the following steps:

1. Determination of the most likely type of accident that occurrence could have escalated to. The so-called key risk areas are airborne collision, aircraft upset, collision on the runway, excursion, fire smoke and pressurization, ground damage, obstacle collision in flight, terrain collision, other injuries, and security.
2. Determination of the potential loss of life category is based on aircraft size and key risk area. The proposed categories are described in Table 7.
3. The selection of the severity score (potential loss of life) from the severity score (Table 7) is based on the input from step 1.

Table 7- Severity Score. Source: Adapted from [17].

Severity Score	Definition
X	A catastrophic accident with the potential for a large number of fatalities (More than 100 possible fatalities).
S	A significant accident with potential for fatalities and injuries (20 to 100 possible fatalities).
M	A major accident with a limited number of fatalities, life-changing injuries or destruction of the aircraft (2 to 19 possible fatalities).
I	An accident involving a single fatality, life-changing injury or substantial damage accident (1 possible fatality).
E	An accident involving minor and serious injury (not life-changing) or minor aircraft damage.
A	No likelihood of an accident.

4. They are identifying the stopping barrier from the ERCS barrier model (Table 8). The stopping barrier prevents the event from escalating into an accident (if it exists).

The ERCS barrier model consists of 8, ordered in a logical sequence, and weighted as per Table 8.

Table 8 - Barriers of the ERCS and their definitions. Source: Adapted from [17].

Barrier Number	Barrier Name	Definiton	Barrier Weight
1	Aircraft, Equipment and Infrastructure Design	Includes maintenance and correction, operation support, the prevention of problems related to technical factors that could lead to an accident.	5
2	Tactical Planning	Includes organisational and individual planning before the flight or other operational activity that supports the reduction of the causes and contributors to accidents.	2
3	Regulations, Processes, Procedures and Compliance	Includes effective, understandable and available regulations, procedures and processes that are complied with (with the exclusion of the use of procedures for recovery barriers).	3
4	Situational awareness and action	Includes human vigilance for operational threats which ensures the identification of operational hazards and effective action to prevent an accident.	2
5	Warning systems operation and action	Warning systems and actions that could prevent an accident and which are fit for purpose, functioning, operational and are complied with.	3
6	Recovery action	Late recovery from a potential accident situation.	1
7	Protections	When an event has occurred, the level of the outcome is mitigated or prevents the escalation of the occurrence by intangible barriers or providence.	1
8	Low Energy Occurance	Scores the same as 'Protections', but for low kinetic energy key risk areas only (ground damage, excursions, other injuries). 'Not applicable' for all other key risk areas.	1

5. It is the identification of the effectiveness of the remaining barriers. The remaining barriers were placed between the stopping barrier and the potential outcome.

The calculation should not consider barriers placed before stopping barriers because they do not prevent the occurrence of an accident. The effectiveness of each barrier shall be classified as described in Table 9.

6. It is the calculation of the barrier weight sum and corresponding barrier score.

The barrier weight sum and corresponding score are calculated by summing the barrier weights for all barriers classified as Stopped, Remaining Know, and Remaining Assumed. So, all barriers scored using the values "Stopped", "Remaining Know", and "Remaining Assumed" collect the points assigned to that barrier. Barriers classified as "Failed Known", "Failed Assumed", or "Not Applicable" will have zero points added to the total sum, as those barriers could not have prevented the accident.

Table 9 – ERCS Barrier model with effectiveness levels and their definitions. Source: Adapted from [17].

Effectiveness level	Definition
Stopped	This is the barrier that prevented the occurrence from escalating into an accident (selected Key Risk Area).
Remaining known	Information in the occurrence report suggests that this barrier was in place and functioning correctly.
Remaining assumed	Normal operating conditions are assumed, under which this barrier is in place and functioning correctly.
Failed known	Information in the occurrence report suggests this barrier did not function properly and so the occurrence escalated towards an accident.
Failed assumed	Based on the information available, it seems that this barrier did not function properly and so allowed the occurrence escalated towards an accident.
Not applicable	The barrier did not exist or was not relevant in the chain of events.

The barrier weight sum corresponds to a score between zero and nine, as shown in Table 10, covering the full range between strong and weak remaining barriers.

Table 10 – Barrier Weight Sum. Source: Adapted from [18].

Barrier weight sum	Corresponding barrier score
No barriers left (Worst likely accident outcome realised)	0
1-2	1
3-4	2
5-6	3
7-8	4
9-10	6
11-12	6
13-14	7
15-16	8
17-18	9

7. Selecting safety score and corresponding numerical risk value from the ERCS matrix in Table 11.

Table 11 – ERCS Matrix. Source: Adapted from [17].

Severity			Classification (ERCS Score)									
Potencial Accident Outcome	**Score**	**Pending Risk Assessment**										
Extreme catastrophic accident with the potential for significant number of fatalities (100+).	X		X9	X8	X7	X6	X5	X4	X3	X2	X1	X0
Major accident with potential for fatalities and injuries (20-100).	S		S9	S8	S7	S6	S5	S4	S3	S2	S1	S0
Significant accident with limited amount of fatalities (2-19), life changing injuries or destruction of the aircraft.	M		M9	M8	M7	M6	M5	M4	M3	M2	M1	M0
An accident involving single individual fatality, life changing injury or substantial	I		I9	I8	I7	I6	I5	I4	I3	I2	I1	I0
An accident involving minor and serious injury (not life changing) or minor aircraft	E		E9	E8	E7	E6	E5	E4	E3	E2	E1	E0
No likelihood of an accident.	A		**No Implication to safety**									
	Corresponding Barrier Score		9	8	7	6	5	4	3	2	1	0
	Barrier Weight Sum		17-18	15-16	13-14	11-12	9-10	7-8	5-6	3-4	1-2	0
			Probability/likelihood of the potencial accident outcome									

The following three colours (Table 12) are used in the ERCS matrix to determine the urgency of the recommended action to be taken about the occurrence.

Table 12 – ERCS Score Meaning. Source: Adapted from [18].

Colour	ERCS Score	Meaning
Red	X0, X1, X2, S0, S1, S2, M0,M1,I0	High risk. Occurrences with the highest risk.
Yellow	X3, X4, S3, S4, M2, M3, I1, I2, E0, E1	Eleveted risk. Occurrences with intermediate risk
Green	X5 to X9, S5 to S9, M4 to M9, I3 to I9, E2 to E9	Low risk occurrences

The matrix's green section represents situations with relatively lower levels of risk. This data can be used to conduct detailed investigations into safety-related occurrences that can potentially increase risk when combined with other events. In other words, the green area of the matrix provides valuable information for analysing and mitigating potential risks.

Each ERCS score is assigned a corresponding numerical value of risk magnitude, which is required to facilitate the aggregation of data and possibly identify trends through the analysis of charts and graphs from the incoming data.

The numerical value of risk magnitude is represented in Table 13.

Table 13 – Numerical value of risk magnitude. Source: Adapted from [17].

ERCS Score	X9	X8	X7	X6	X5	X4	X3	X2	X1	X0
Corresponding numerical value	0.001	0.01	0.1	1	10	100	1000	10000	100000	1000000
ERCS Score	S9	S8	S7	S6	S5	S4	S3	S2	S1	S0
Corresponding numerical value	0.0005	0.005	0.05	0.5	5	50	500	5000	50000	500000
ERCS Score	M9	M8	M7	M6	M5	M4	M3	M2	M1	M0
Corresponding numerical value	0.0001	0.001	0.01	0.1	1	10	100	1000	10000	100000
ERCS Score	I9	I8	I7	I6	I5	I4	I3	I2	I1	I0
Corresponding numerical value	0.00001	0.0001	0.001	0.01	0.1	1	10	100	1000	10000
ERCS Score	E9	E8	E7	E6	E5	E4	E3	E2	E1	E0
Corresponding numerical value	0.000001	0.00001	0.0001	0.001	0.01	0.1	1	10	100	1000

Despite the ERCS being one of the most complete risk assessment tools, there is still room for improvement. Like the ERC classification, there might be data gaps in the safety risk assessment process. This study addresses these data gaps and promotes continuous ERCS improvement and the development of new and innovative approaches.

An ERCS risk assessment template is shown in Annex B.

2.3.3. BowTie Methodology

BowTie analysis is a risk analysis method used to manage and reduce risks. This process starts by observing a potential risk and splitting it into two categories: one that includes all the potential contributing factors and lists all the potential consequences.

According to [19], the BowTie methodology has several goals:

- Provide a structure to analyse a hazard systematically.
- Help decide whether the current level of control is sufficient (or whether risks are as low as reasonably practicable).
- Help identify where and how investing resources would have the greatest impact.
- Increase risk communication and awareness.

It is represented through a BowTie diagram, a visual tool that displays the various factors that contribute to a particular event or outcome, as well as the controls that can be put in place to prevent or mitigate its occurrence. It provides a clear and concise overview of the causal relationships between the causes and effects of an event, allowing for a comprehensive analysis of the situation at hand. While it can be created based on pre-existing fault and event trees, a team often develops collaboratively in a workshop setting to ensure that all relevant factors are considered. A BowTie diagram simplifies the complexity of analysing an event by presenting its causes, consequences, and potential preventive measures (controls) in a clear and easy-to-understand format [6].

The BowTie diagram is constituted of several elements, as mentioned by [19]:

- Hazard: The BowTie starts with the hazard.
- Event: the loss of control of the hazard.
- The source of Risk is depicted on the left side (customarily the prevention side) of the BowTie diagram.
- The consequences of loss of control of the hazard are depicted on the right side (customarily the mitigation side) of the BowTie diagram.
- Prevention controls on the left side of the diagram represent prevention barriers, which stop threats from resulting in the top event.
- Reactive Controls shown to the right of the top event represent mitigation barriers, which mitigate the top event (i.e., reduce the scale of and possibly stop undesired consequences).
- Escalation Factors can be applied to both prevention and mitigation barriers, leading to impairment or failure of the barrier to which they are attached.
- The barrier to Escalation mitigates the escalation factors, helping maintain the main pathway barrier at its intended function. Degradation controls can but do not necessarily satisfy the effective, independent, and auditable barrier criteria.

An example of a complete Bowtie methodology diagram is represented in Figure 7.

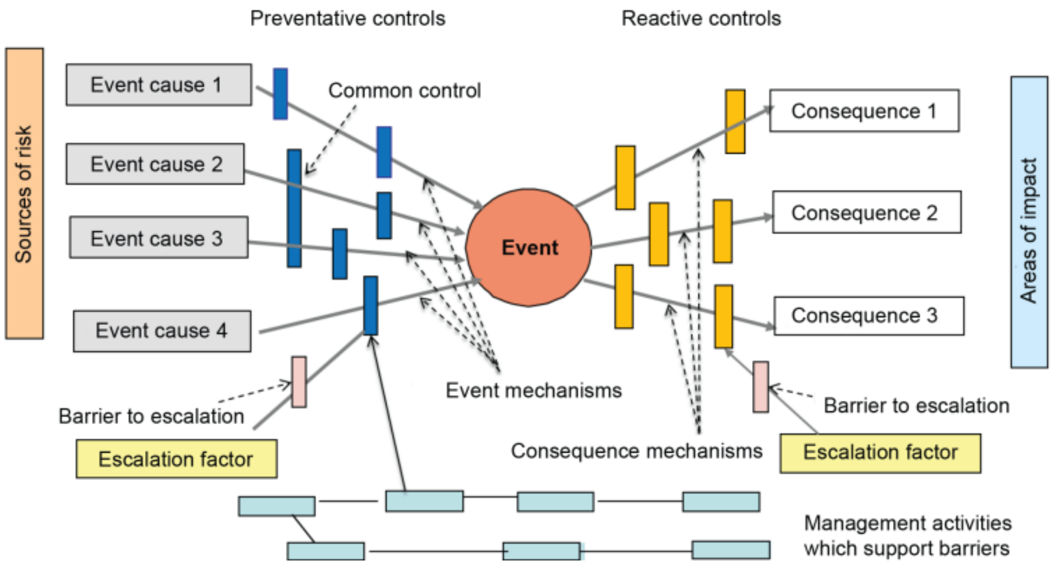

Figure 7 – Example of BowTie Methodology Diagram [6].

In Annex C, an example used in the aviation industry is presented.

2.3.4. Risk Assessment Over Conflict Areas

There are armed confrontations all around the world, both declared and undeclared. In these warfare zones, things can happen quickly, escalating and de-escalating with little to no notice. While an armed conflict will almost certainly present a risk to aircraft operating there, there may also be an increased risk for aircraft passing near or over the conflict zone.

When considering the risk associated with flying over or near conflict zones, certain general assumptions can be made regarding the elements of a risk assessment. The first assumption is that the potential consequences of successfully downing a civil aircraft are severe in terms of the loss of life and the economic impact of such an attack. Secondly, it can be assumed that once a civil aircraft is on a designated flight path at cruising altitude and a surface-to-air missile (SAM) is deployed, there are typically no viable actions that can be taken to mitigate the risk. Therefore, in conflict zones, the most critical aspect of risk assessment revolves around the threat itself. According to [20], the key driver for a risk assessment over conflict areas is the threat likelihood derived from an attack's capability and intent.

The capability of an attack encompasses weapon systems that, in the context of posing a threat to an overflying civilian aircraft, might include surface-to-air-missile (SAM) systems, man-portable air defence systems (MANPADS), and anti-aircraft artillery (AAA).

The intent is an assessment of the likelihood that a weapon system would be used against a specific target or group of targets. However, capability can be underestimated, intent can be misinterpreted, targeting mistakes can occur in the fog of war, and non-combatants can be misidentified and inadvertently fired upon.

The collection of relevant information, the subsequent threat analysis, the security risk assessment, the hazard identification, the safety risk assessment, and the risk determination constitute the necessary steps in the continuous risk assessment cycle. This cycle involves specific processes and decisions to address all aspects of risk exposure.

Figure 8 represents the risk assessment cycle and the flowchart necessary to interpret and execute a robust risk assessment over conflict areas.

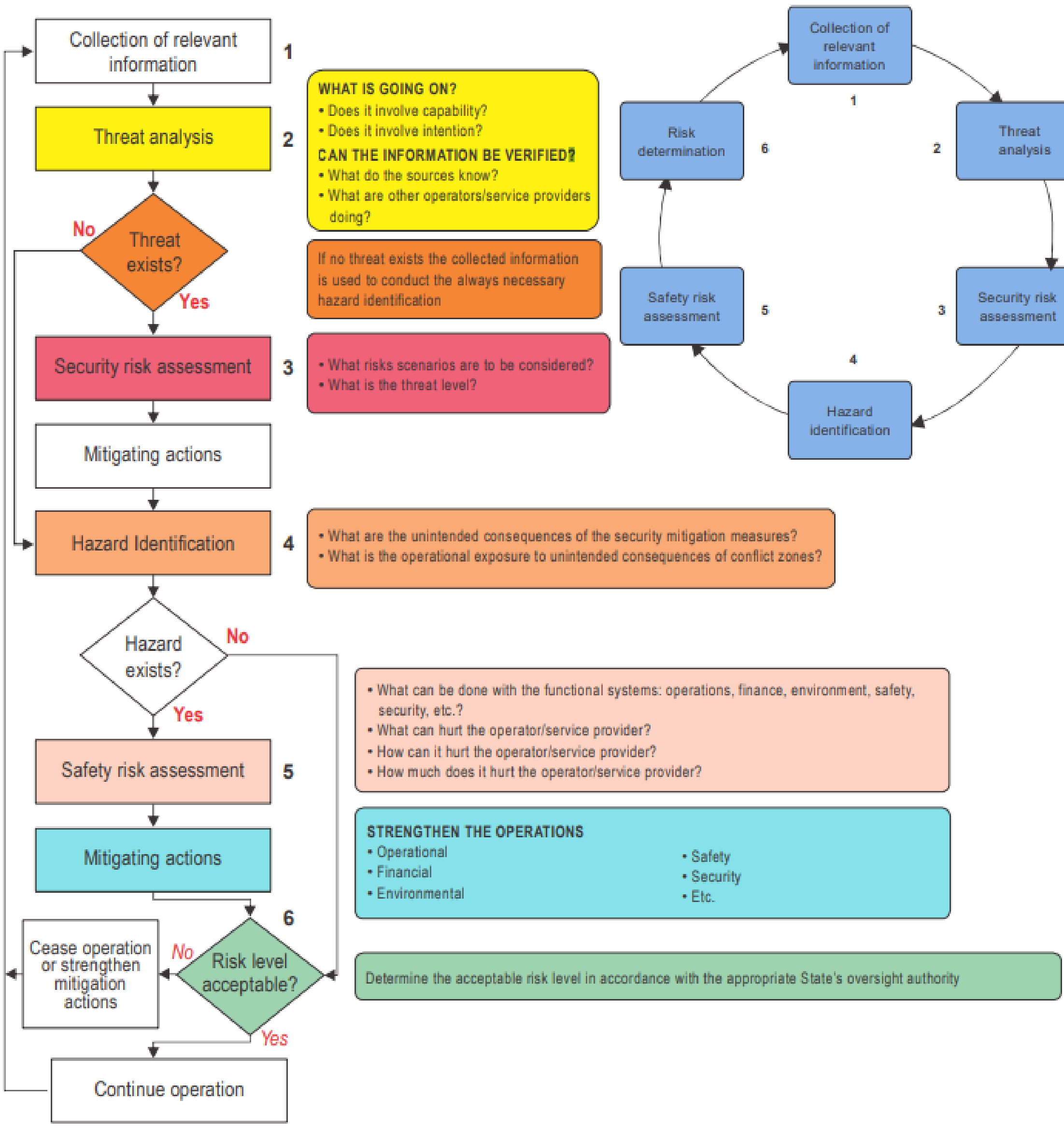

Figure 8 - Flow chart of the risk assessment cycle [20].

2.3.4.1. Use of Artificial Intelligence for risk management to predict conflict areas

Using advanced computing techniques, organisations can gather data from over 200,000 open sources in more than 60 different languages in a few minutes. This dataset then enables qualified and objective assessments of the impact and probability of any incident type, thus producing a highly accurate risk assessment. Analysts can then guarantee a correct global picture of the aviation security environment. AI (Artificial Intelligence) can process vast amounts of data from multiple sources, such as satellite imagery, radar data, social media, news reports, and intelligence reports. AI systems can identify patterns and potential risks in conflict areas more effectively than manual analysis by fusing and analysing this information. In addition, AI systems can continuously monitor conflict areas in real-time, allowing aviation authorities and airlines to stay informed about any sudden changes or developments that could affect flight safety.

This integration between the analysts and the software, combined with machine learning algorithms and AI, ensures the system improves continuously. This AI system is still under development. Currently, EASA is working on the regulations and guidelines to introduce AI in the aviation industry.

2.3.5. Seven Steps Process

According to the UK CAA (United Kingdom Civil Aviation Authority), risk assessment and mitigation barriers require a systematic approach. The complete process can be divided into seven steps. These are:

1. System description.

It describes the system or activity under assessment, including its components, functions, and interactions.

2. Hazard and consequence identification.

It identifies and lists all potential hazards associated with the system. Moreover, this involves identifying sources of harm or events that could lead to undesirable consequences. It should be initiated at the earliest possible stage. The level of detail required will depend on the complexity of the system under consideration and the stage of the system lifecycle at which the assessment is being carried out. Hazard identification can be carried out through three generic approaches:

a. The historical uses and analysis of the existing hazard logs and The incident/accident reports.
b. Brainstorming planned and organised sessions aimed at encouraging a team of participants with various relevant experiences and expertise to creatively explore the system for potential hazards.
c. The Systematic hazard identification processes include failure mode and effect analysis (FMEA) or hazard and operability study (HAZOP).

3. The severity of the consequences estimation of the occurring hazard.

Assesses the severity of the consequences that may arise if each hazard occurs. Consider potential impacts on people, the environment, property, and other relevant factors. The severity classification for all credible hazard consequences should be determined and clearly defined in a table. Table 14 shows the severity classification scheme example proposed by the UK CAA.

Table 14 – Severity of consequences. Source: Adapted from [21].

Aviation Definition	Meaning	Value
Catastrophic	Aircraft / Equipment destroyed. Multiple deaths.	5
Hazardous	A large reduction in safety margins, physical distress or a workload such that organisations cannot be relied upon to perform their tasks accurately or completely. Serious injury or death to a number of people. Major equipment damage.	4
Major	A significant reduction in safety margins, a reduction in the ability of organisations to cope with adverse operating conditions as a result of an increase in workload, or as a result of conditions impairing their efficiency. Serious incident. Injury to persons.	3
Minor	Nuisance. Operating limitations. Use of emergency procedures. Minor incident.	2
Negligble	Little consequence.	1

4. The Likelihood Estimation/Assessment of the hazard occurring consequences.

The Likelihood Estimation/Assessment of the hazard occurring consequences involves considering historical data, expert judgement, industry standards, and any other available information to estimate the likelihood of each identified hazard. The proposed probability or likelihood classification (Table 15) specifies the likelihood as qualitative categories but also includes numerical values for the probabilities associated with each category. In some cases, data may be available, allowing direct numerical estimates of the likelihood of failure.

Table 15 - Likelihood of occurrence. Source: Adapted from [21].

Qualitative Definition	Meaning	Value
Frequent	Likely to occur many times (has occurred frequently).	5
Occasional	Likely to occur sometimes (has occurred infrequently).	4
Remote	Unlikely, but may possibly occur (has occurred rarely).	3
Improbable	Very unlikely to occur (not known to have occurred).	2
Extremely Improbable	Almost inconceivable that the event will occur.	1

5. Evaluation of the risk.

It combines the severity of consequences and the likelihood of occurrence to evaluate the overall level of risk associated with each hazard. The proposed risk matrix is shown in Table 16.

Table 16 – Risk Tolerability Matrix. Source: Adapted from [21].

Severity						
Catastrophic	5	5 Review	10 Unacceptable	15 Unacceptable	20 Unacceptable	25 Unacceptable
Hazardous	4	4 Acceptable	8 Review	12 Unacceptable	16 Unacceptable	20 Unacceptable
Major	3	3 Acceptable	6 Review	9 Review	12 Unacceptable	15 Unacceptable
Minor	2	2 Acceptable	4 Acceptable	6 Review	8 Review	10 Unacceptable
Negligible	1	1 Acceptable	2 Acceptable	3 Acceptable	4 Acceptable	5 Review
		Extremely improbable	Improbable	Remote	Occasional	Frequent
		1	2	3	4	5
				Likelihood		

The risk classification is characterized by the following Table 17.

Table 17 – Risk Classification. Source: Adapted from [21].

Acceptable	The consequence is so unlikely or not severe enough to be of concern; the risk is acceptable. However, consideration should be given to reducing the risk further to as low as reasonably practicable to further minimise the risk of an accident or incident.
Review	The consequence and/or likelihood is of concern; measures to mitigate the risk to as low as reasonably practicable should be sought. Where the risk is still in the review category after this action then the risk may be accepted, provided that the risk is understood and has the endorsement of the individual ultimately accountable for safety in the organisation.
Unacceptable	The likelihood and severity of the consequence are intolerable. Major mitigation will be necessary to reduce the likelihood and severity of the consequences associated with the hazard

6. The risk mitigation and safety requirements measures.

Develops and implements suitable risk mitigation measures to reduce the identified risks. It needs to apply the As Low as Reasonably Practicable (ALARP) principles, and some strategies for risk mitigation include:

a. Revision of the system design.
b. Modification of operational procedures.
c. Changes to staffing arrangements.
d. Training of personnel to deal with the hazard.
e. Development of emergency and/or contingency arrangements and plans.

According to the UK CAA, "as low as reasonably practical" can be defined as when the cost of further risk reduction measures or the cost of assessing the potential improvement in risk reduction is higher than the anticipated costs associated with the existing risk, it is not justified to pursue additional risk reduction efforts.

The effectiveness of any proposed risk mitigation measures must be assessed by examining closely whether the implementation of the mitigation measures might introduce any new hazards or change the basis on which other assessments have been made.

It is a risk management principle used in various industries to assess and manage risks. The principle is that the residual risk (the amount of risk that remains after controls are accounted for) shall be reduced as far as reasonably practicable.

7. Claims, arguments, and evidence that the safety requirements have been met and documenting this in a safety case.

Presents claims, arguments, and evidence demonstrating the safety requirements have been met. Document this information in a safety case, which serves as a comprehensive record of the risk assessment process, mitigation measures, and evidence supporting their effectiveness. This step also promotes a second evaluation after the mitigation measures are put in place to evaluate the residual risk following, this way, the ALARP principles.

2.3.6. Failure Mode and Effect Analysis (FMEA)

The Failure Mode and Effect Analysis (FMEA) is a continuous improvement methodology that enables analysts to examine potential failures in advance, foresee their effects, and take corrective action. It solves the query, "What happens next if this component fails?". In the late 1940s, it was first used to organize military activities. Since then, FMEA has been used in various industries to evaluate the dependability of systems, from the automotive sector, where it first gained notoriety, to aviation and technology.

The FMEA analysis applies to human, equipment, and system failure modes as well as software, hardware, or processes, and its goal is to identify and remove a failure's fundamental causes to reduce the risk of a failure happening.

The first step to conducting a successful FMEA is to analyse functional requirements and their effects to identify all failure modes. Failure modes in one component can induce them in others.

The second step is to determine severity (S), which is the seriousness of failure consequences of failure effects.

The usual failure effect severity (S) practice rates on a scale of 1 to 10, where 1 is the lowest severity and 10 is the highest, as shown in Table 18.

Table 18 – Failure Effect Severity (S). Source: Own Elaboration

Rating	Meaning
1	No effect, no danger.
2	Very minor- usually noticed only by discriminating.
3	Minor- only minor part of the system affected.
4-6	Moderate- most users are inconveniencied and/or annoyed.
7-8	High- loss of primary function.
9-10	Very High- hazardous. Failure constitutes a safety hazard and can cause injury or death.

The third step is to assess the probability number (O), which means examining each failure mode's cause(s) and how often the failure occurs.

Failure modes are assigned an occurrence ranking from 1 to 10, as shown in Table 19.

Table 19 – Occurrence (O) Rating. Source: Own Elaboration

Rating	Meaning
1	No doccumented failures.
2-3	Low- relatively few failures.
4-6	Moderate- some occasional failures.
7-8	High- repetead failures.
9-10	Very High- failure is almost certain.

The fourth step is assigning a detection number (D), which indicates how likely failures will be detected and ranks the ability of identified actions to remedy or remove defects or detect failures.

The detection number (D) ranges from 1 to 10, where 1 is a certain fault, and 10 is a fault that could be undetected, as shown in Table 20.

Table 20 – Detection Value (D) Rating. Source: Own Elaboration.

Rating	Meaning
1	Fault is certain to be caught by testing.
2	Fault is almost certain to be caught by testing.
3	High probability that tests will catch the fault.
4-6	Moderate probability that tests will catch the fault.
7-8	Low probability that tests will catch the fault.
9-10	Fault will be passed undetected.

The final step is calculating the risk priority number (RPN). This value comes from this formula $RPN = S \times O \times D$.

Results should reveal the most problematic areas, and the highest RPNs should get the highest priority for corrective measures.

In the following Figure 9, it is represented the process steps needed to complete a robust FMEA.

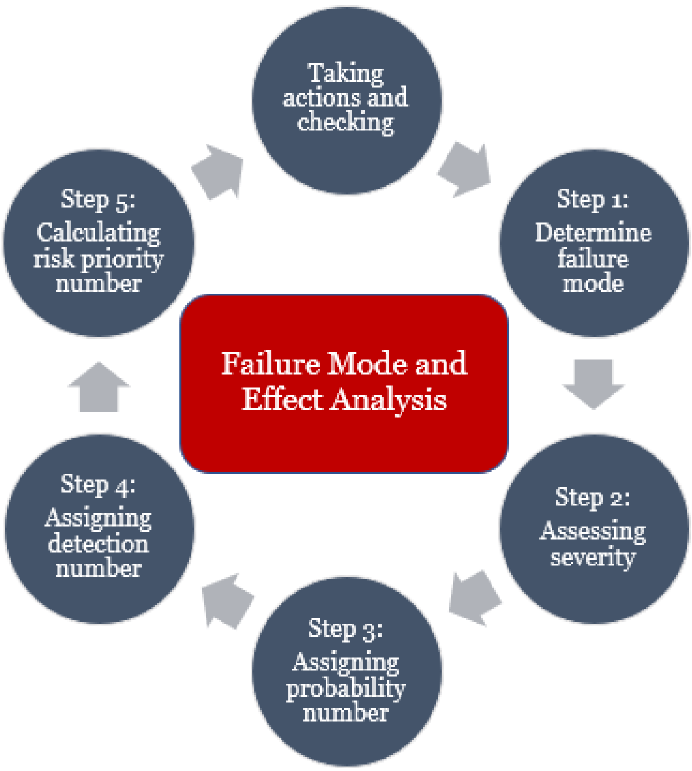

Figure 9 – FMEA process steps. Source: Adapted from [22].

By consistently employing FMEA, companies can achieve a range of benefits. Firstly, it helps prevent failures altogether, leading to enhanced trust and increased customer satisfaction. Additionally, FMEA serves as a repository of corporate knowledge by documenting past experiences related to similar products and processes. This valuable history can be leveraged to facilitate future improvements and serve as a reference point for ongoing enhancement initiatives.

Any product, initiative, or organisation's results are directly impacted by its implementation.

For all its benefits, the FMEA does have a few limitations. For instance, it is only as excellent as the team that created it. Problems that team members are unaware of won't likely be found or fixed, constituting unknown unknowns.

Another limitation is that the FMEA's methodology for ranking failure modes is in order of risk. FMEA is a valuable tool in identifying and mitigating failure modes; it alone may not be sufficient to eliminate all potential failures. Additional measures and actions might be necessary to effectively address the identified failure modes and ensure comprehensive safety management.

2.3.7. Root Cause Analysis (RCA)

Root cause analysis (RCA) is a systematic process used to identify an event's underlying cause or causes and prevent similar events from occurring. RCA is a key tool used in aviation safety to identify the root causes of accidents, incidents, and other safety-related events. Preventing the next event or accident is the objective of a root cause analysis.

By addressing root causes, organisations can take proactive steps to prevent similar events from occurring in the future, which improves safety and reduces the risk of accidents and incidents.

According to [23], the RCA process involves the following steps:

1. Gathering information: The first step in RCA is to gather all relevant information about the event; this includes data from the aircraft's cockpit voice recorder (CVR) and flight data recorder (FDR), witness statements, maintenance records, weather reports, and other relevant sources.
2. Defining the problem: Once all the information has been collected, the problem must be defined clearly and precisely; this involves identifying the specific event or situation that needs analysis.

3. Identifying contributing factors: The next step is identifying all the factors contributing to the event. Moreover, this includes immediate causes (e.g., mechanical failure, pilot error) and underlying causes (e.g., organisational culture, inadequate training).
4. Identifying the root cause: The event's root cause is identified using the information gathered in the previous steps; this is the fundamental reason why the event occurred, and it must be addressed to prevent similar events from happening.
5. Developing corrective actions: Once the root cause has been identified, corrective actions can be developed to prevent similar events from occurring in the future. These actions may include policies, procedures, training, or equipment changes.
6. Implementing corrective actions: The final step is implementing them and monitoring their effectiveness over time; this may involve revising procedures, providing additional training, or making other changes to improve safety.

The most common technique for representation of the root cause analysis is the fishbone diagrams, also known as cause-and-effect diagrams or Ishikawa diagrams, as shown in Figure 10.

The term "fishbone diagram" originates from its resemblance to a fish, featuring a head and multiple fins. Each "fin" or "branch" within the diagram represents a distinct category relevant to the situation. In aviation SMS databases, commonly employed categories include human factors, machinery, systems, policies and procedures, materials, organisation, and environment.

The head of the fishbone describes the hazard/Top Event.

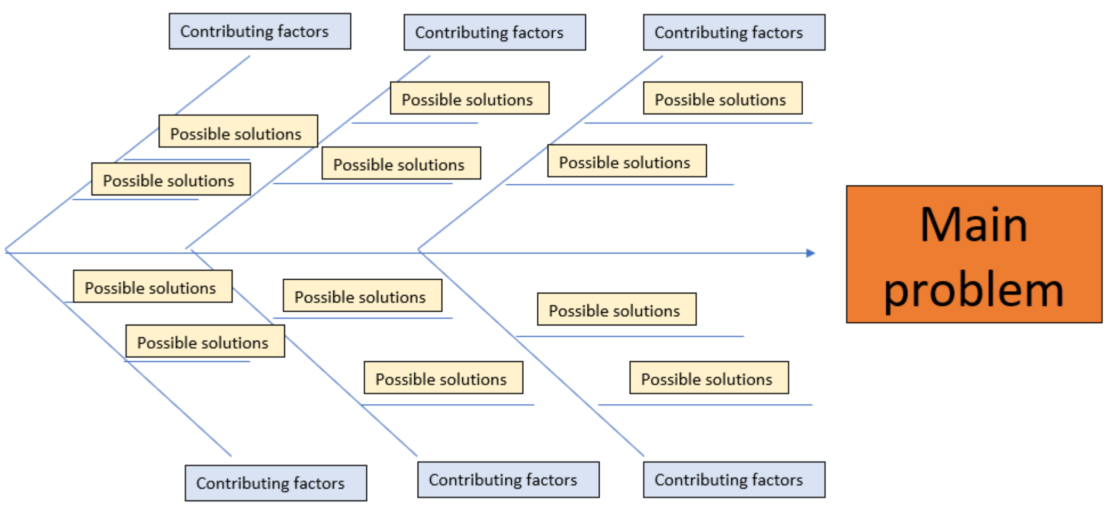

Figure 10 – Fishbone Diagram Example [24].

The main advantages of the root cause analysis are:

- Once you identify the root cause of an incident or accident, you can find a permanent solution to reduce or eliminate the probability of a reoccurrence.
- It aids in the development of a systematic and logical approach to problem-solving. Once the main cause of a defect or issue is identified, the next step is to utilize existing information to determine and explore major problem-solving approaches.
- We can identify current needs as well as future needs for the improvement of the organisation and system.
- It helps develop proper, repeatable, step-by-step processes and allows for the confirmation of results from one process by another.

On the other hand, the main problem of the root cause analysis is that it only assumes and focuses on one cause of the defect. However, the case may be more complicated. There could be several root causes of a problem. Therefore, one must concentrate on all fault elements and consider all its causes.

2.3.8. Fault Tree Analysis (FTA)

Fault Tree Analysis (FTA) is a systematic approach to identifying and analysing potential failures in complex systems. It aims to comprehend the causal connections associated with a primary event representing a potential danger. It systematically reveals subsequent layers using a consistent questioning approach, ensuring the identification of all contributing factors and underlying causes. It was originally developed in 1962 at Bell Laboratories by H.A. Watson to evaluate an intercontinental ballistic missile (ICBM) launch control system. In 1966, Boeing started using the analysis for civil aircraft design. It is widely used in aviation safety to assess and manage risks associated with various operational and maintenance processes.

According to the steps involved in conducting an FTA for aviation safety risk assessment:

1. Define the Top Event: The top event is the primary undesired event you want to prevent. In aviation safety, the top event could be an accident, an incident, or any other event that poses a risk to the safety of the aircraft, passengers, or crew.
2. Identify the Basic Events: Basic events are the events or conditions that can lead to the occurrence of the top event. These events could be failures in equipment, procedures, or human error. The basic events are identified through brainstorming, checklists, and other data sources.

3. Construct the Fault Tree: The fault tree represents the basic events and their relationships with the top event. The fault tree is constructed by starting with the top event and working backwards to the basic events.
4. Analyse the Fault Tree: Once the fault tree is constructed, the next step is to analyse it to determine the probability and consequences of the top event. This analysis is done using probability calculations and other risk assessment techniques.
5. Identify Mitigation Measures: Based on the fault tree analysis, mitigation measures are identified to prevent or minimize the occurrence of the top event. Mitigation measures could include changes in equipment, procedures, or training.
6. Implement Mitigation Measures: The final step is implementing the mitigation measures identified in Step 5. The effectiveness of the mitigation measures should be monitored and evaluated regularly to ensure that the risk level remains within acceptable limits.

Fault-tree analysis diagrams utilize Boolean logic (a system of logical thought used to create true/false statements [25]) and employ symbolic representations to depict potential causes or factors that may have led to a failure. These representations encompass both external events and conditioning events. The connections between these events are facilitated by gate symbols such as "and" and "or" to define the relationships between the input and output events.

Figure 11 below shows the list of symbols used in FTA.

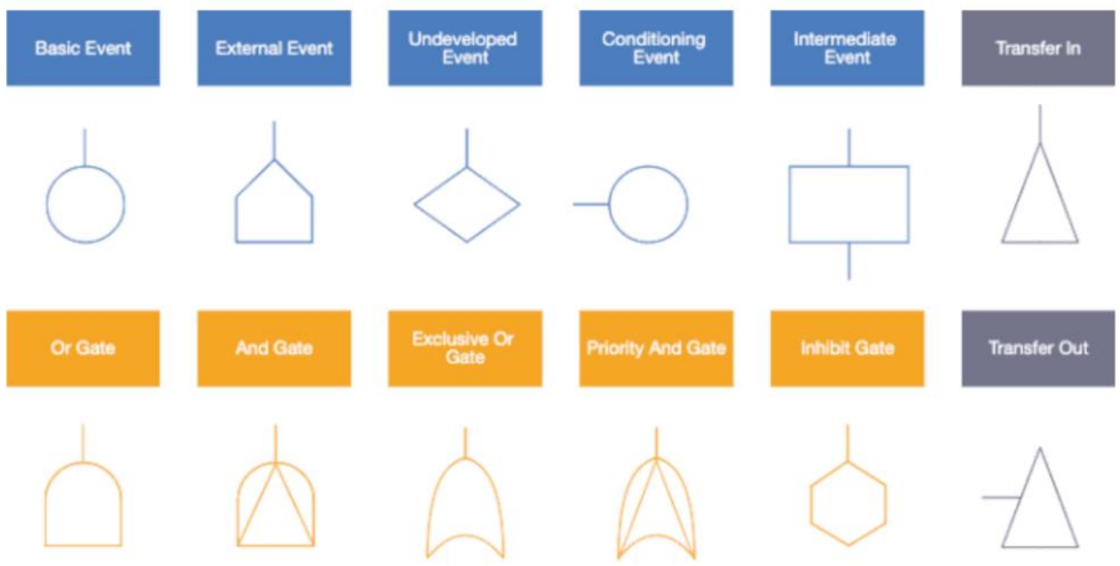

Figure 11 – FTA Symbols Representation [26].

The FTA shows how basic events interact, leading to the overall failure. The example in Figure 12 shows the case of the ZS-CME (bombardier CRJ-100 from CemAir) serious incident. This aircraft suffered a main landing gear wheel disintegration upon landing, and Figure 12 describes how different failures are connected underneath until the basic events are reached. Basic events are the root causes of such failures, leading to the overall failure under investigation.

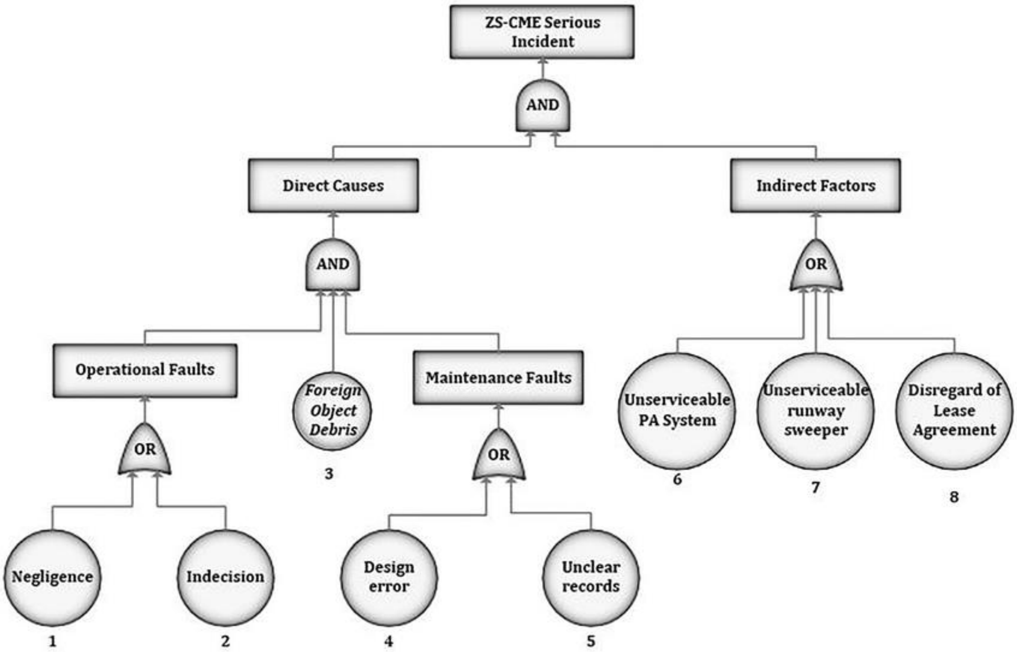

Figure 12 – FTA Diagram Representation [27].

FTA offers several advantages and disadvantages in assessing and managing risks described in Table 21 below.

Table 21 – Advantages and Disadvantages of FTA. Source: Adapted from [26].

Strenghts	Weakness
The fault tree visually depicts the analysis that will help the team to work on the cause of an event in a logical way that leads to failure and highlights the critical components related to system failure	The need to foresee and evaluate first the undesired event. Therefore, the contributing factors to the cause must be anticipated.
Easier and efficient way to analyse the system	Expensive and time-consuming
Suitable for both qualitative and quantitative data	If the reader doesn't possess skills, then FTA may not be desirable to use.

2.3.9. Brainstorming

Brainstorming in risk assessment is a creative and collaborative technique used to generate a wide range of ideas and identify potential risks associated with a specific project, activity, or process. It is considered a relatively quick and easy means of collecting ideas surrounding a particular assessment for further analysis. Sessions can be performed one-on-one or by a qualified, knowledgeable group of stakeholders. It aims to stimulate and generate a free-flowing dialogue to identify potential failure modes, hazards, risks, and possible controls. Brainstorming is conducted in a structured or unstructured fashion. In a structured session, each person is required to offer an idea as their turn arises. An "unstructured" brainstorming approach relies on spontaneity, allowing the group to provide ideas as they come to mind, which can create a more relaxed atmosphere. However, this approach can allow more vocal members to dominate the session, causing other viewpoints and ideas to be overshadowed. In either case, to be effective, brainstorming sessions must ensure an environment free of judgment of ideas/items.

Usually, general brainstorming follows five process steps to get an efficient and practical result. According to [28], these steps can be adapted for risk assessment brainstorming, resulting in an easy and flexible tool for risk assessment. The five process steps are:

1. **Be clear about the problem** – gather as much information as possible about the assessment and make it clear to all stakeholders.
2. **Collect your tools** – Create mind maps, tables, and formulas to manage the ideas better.
3. **Focus on ideas** – Brainstorming can lead to other conversations and divert from the main goal.
4. **Narrow down our list** - After you've made your list or mind map of ideas, aim to narrow it down to your 2-3 best ideas.
5. **Present your findings** – Present the main findings to the administration once the assessment is made.

A mind map, flowcharts, or matrixes usually represent brainstorming. These representations help organise and categorise the identified risks, facilitating further analysis and prioritization.

The main advantages and disadvantages are described in Table 22.

Table 22 - Advantages and Disadvantages of the Checklist method. Source: Adapted from [29].

Strenghts	Weakness
Easily recognizing as one ideia inspires the next	Ideas and viewpoints maybe overshadowed
Lots of risks are quickly recognized	Some risks can be missed
Participants need not be afraid that their ideas will be evaluated during the session	Some participants need longer to understand the theme and can't immediately provide ideas.
The rules of brainstorming are already familiar	The results of brainstorming are largely groupthink and not necessarily individual thoughts or ideas.

2.3.10. Checklist

Checklists typically consist of specific items or "yes/no" questions derived from published standards, codes, and industry practices for a specific application. Individuals or teams use checklist analysis to identify deviations and hazards in a process or system. This method is relatively easy to use and cost-effective; however, the analysis's quality depends upon the checklist's quality and content. For a checklist to be effective, it must target specific concerns, standards, or practices of the process or system being analysed.

Checklists usually follow four process steps as described in Figure 13:

1. **Define purpose and scope** - The stakeholders define the purpose and scope of the analysis.
2. **Select/construct a checklist** - Experienced stakeholders examine the subject to be analysed and select an existing checklist, if available or construct a specific list of items or questions to address potential hazards.
3. **Perform checklist analysis** - Each team member takes their turn to make suggestions and ideas related to the question/problem statement; this can be done randomly in an unstructured session or a structured order.
4. **List hazards and needed controls** – Due to the checklist review, a scribe is assigned to record each idea on a laptop projector, whiteboard, or flip chart with the display visible to all participants. Team members must see the list of ideas to stimulate additional thoughts and ideas.

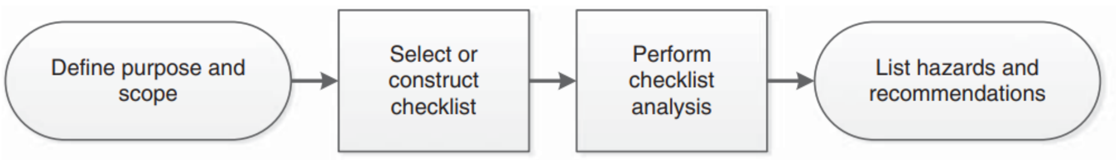

Figure 13 – Checklist process steps. Source: Own Elaboration.

Table 23 represents the advantages and disadvantages of checklist risk assessment.

Table 23 - Advantages and Disadvantages of the Checklist method. Source: Adapted from [30].

Strenghts	Weakness
Ease of use	Quality of analysis depends on the quality of the checklist
Limited training or preparation required	Omissions on the checklist can result in missed potential hazards.
Quick and cost effective	May not be suited for more complex situations
Easy to delegate tasks	Specific and complete checklist.
Easy to follow the order	Knowledgeable individual to perform checklist

Brainstorming and checklist analysis can be considered interconnected because the main way to develop a checklist analysis is through brainstorming the main hazards and risks associated with the operation.

2.3.11. Monte Carlo Simulation

Monte Carlo Simulation is a computerized mathematical technique that allows risk to be accounted for in quantitative analysis and decision-making [31].

A Monte Carlo Simulation is used to model the probability of different outcomes in a process that cannot easily be predicted due to the intervention of random variables. It is a technique used to understand the impact of risk and uncertainty. It is used to tackle many problems in many fields, including investing, business, physics, and engineering. It is also referred to as a multiple probability simulation.

The Monte Carlo Simulation process typically involves the following steps:

1. Define the problem: Clearly define the system or process to be modelled and the objective of the simulation.
2. Develop a model: Create a mathematical or computational model that describes the system's behaviour or process under study.
3. Define input parameters: Identify the key input parameters that influence the behaviour of the system or process. These parameters can be random or deterministic and may be represented by probability distributions.
4. Generate random samples: Generate many random samples for each input parameter based on their probability distributions.
5. Run simulations: Use the model to simulate the system's behaviour or process using random samples of input parameters.
6. Analyse results: Analyse the results of the simulations to obtain statistical information about the behaviour of the system or process, such as mean values, standard deviations, percentiles, and confidence intervals.
7. Validate the model: Test it to ensure that it accurately represents the behaviour of the system or process under study.

8. Conclude: Use the results of the simulations to draw conclusions about the behaviour of the system or process and make decisions based on these conclusions.

Usually, the Monte Carlo Simulation is represented through software, flowcharts, and Excel templates. These representations are modelled according to the type and goal of the risk assessment.

The main advantages and disadvantages of the Monte Carlo Simulation are described in Table 24 below.

Table 24 – Advantages and Disadvantages of Monte Carlo Simulation. Source: Adapted from [32].

Strenghts	Weakness
Can model complex systems	No interactive link between data and parameters
Intituive and relatively easy to implement	Approximate technique (simulation technique)
Time to results reasonably short	Unidirectional
Widely accepted and used	Does not allow "backwards reasoning"
All kinds of probability distributions can be used	Validition usually ad hoc

Ad hoc typically signifies a solution for a specific purpose, problem, or task rather than a generalized solution adaptable to collateral instances [33].

"Backwards reasoning" is to think backwards. Start from what you want and then seek supporting logic [34].

2.4. Conclusion

Current risk assessment methods despite being studied and developed over many years, there are still many aspects that are beyond "human control" due to the inability to identify all possible dangers and scenarios. The development of AI can combat this problem as described further below.

In summary, Chapter 2 overviewed the current risk assessment methods used in the aviation industry and exposed the main features, guidelines, advantages and disadvantages of each method. The first part of the chapter describes an SMS framework proposed by ICAO, with the inclusion of a default risk assessment method (section 2.2.3). The last part describes eleven risk assessment methods suitable for Hi Fly. In the next chapter, Hi Fly's SMS and the Safety department organisation are described.

3. Chapter 3 - Safety Management System at Hi Fly

3.1. Safety Department Organisation at Hi Fly

Hi Fly Safety Department includes the Accountable Manager (AM), a Safety Manager (SM), a Compliance Monitoring Manager (CMMer), a Safety Review Board (SRB), a Safety Action Group (SAG), and a Departmental Safety Action Group, according to the diagram shown in Figure 14.

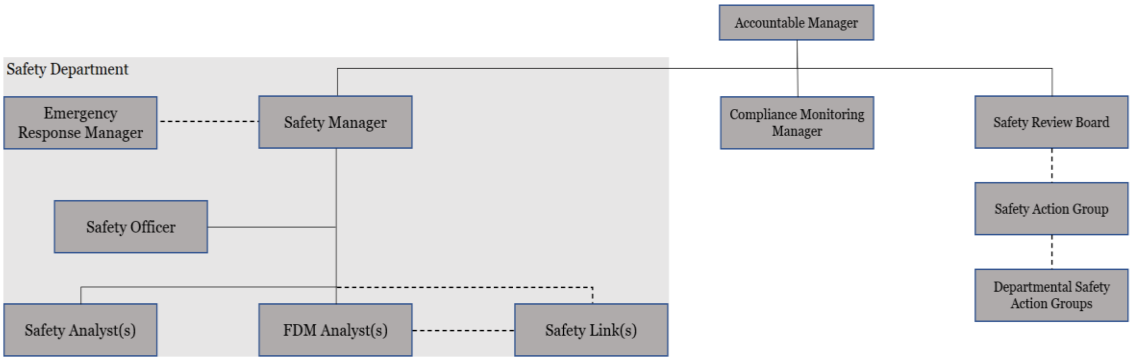

Figure 14 – Hi Fly's safety management organisation diagram. Adapted from [35].

The AM is accountable for the performance, implementation, and maintenance of the SMS throughout Hi Fly. It has the authority to make important policy and financial decisions necessary to ensure all operations' overall safety and security. He is responsible for ensuring that all operations and maintenance activities are conducted in compliance with the requirements of the relevant aviation regulatory authority, such as ANAC, TM-CAD, or other applicable authorities, and additional Hi Fly requirements to maintain the validity of the AOC (Air Operator Certificate).

According to the Hi Fly Safety Management Manual (SMM), to fulfil his responsibility, the AM needs to:

- Establish and promote the Safety Policy.
- Ensure that all the components of the SMS are in place (provided with adequate facilities, workplace, equipment, and supporting services) and functioning properly.
- Ensure the planning and allocation of adequate financial, human, and physical resources necessary to manage safety and security risks to Hi Fly operations and activities.

- Resolve operational and continuing airworthiness safety, security, and quality issues.
- Ensure that Hi Fly operations and activities are conducted by the conditions and restrictions of the AOC, the certificate for the management of continuing airworthiness, and in compliance with applicable regulations and Hi Fly standards.

The SM serves as the representative of the AM for all matters related to operational safety. Their responsibilities include promoting and supervising safety, providing regular reports to the AM, and ensuring compliance with regulatory requirements to maintain a safe operating environment.

The person must also report to the relevant authorities to ensure that all safety-related matters are properly addressed and managed.

His duties and responsibilities to ensure the oversight of the SMS are:

- To provide information and advice on safety matters to the AM.
- To provide support and consultation on safety management to all departments.
- To prepare, update, and disseminate the SMM.
- To conduct daily activities regarding the SMS of the operator and ATO.
- To ensure the efficient performance of the mandatory and Voluntary reporting scheme.
- To facilitate hazard identification and risk assessment.
- To develop and monitor the performance of the Safety Action Plan.
- To act as secretary of the SAG.
- To liaise with relevant authorities on safety issues.
- To comply with all applicable regulations related to SMS.
- To maintain an open liaison with regulatory and investigation bodies, manufacturers, and safety organisations.
- To promote periodic safety-related meetings.
- To provide periodic reports on safety performance.
- To ensure that all personnel receive adequate SMS training and education.
- To ensure the initiation and follow-up of internal occurrence/accident investigations.
- To ensure the maintenance and recording of all safety-related documentation and reports.
- To manage the ERP and report its status to the AM.

- To manage the Fight Safety Analysis Program and report its performance to the AM.
- To participate and represent Hi Fly at industry-related meetings and events.

The SM is assisted by:

- The Safety Officer, in all safety-related duties, with a special focus on Risk Management.
- The Safety Analyst is responsible for analysing all the safety-related data obtained across Hi Fly as part of the SMS.
- The Flight Data Monitoring (FDM) Analyst is responsible for ensuring the collection of all the flight data and related procedures.

The Safety Link relates to anyone outside the Safety Department with relevant knowledge and expertise in a specific technical or non-technical domain. The Safety Department can request the participation of the Safety Link to assist in the analysis of identified safety issues arising from, but not limited to, the internal safety reporting scheme, flight data monitoring program, safety audits, etc.

The Safety Review Board (SRB) is a high-level strategic committee that monitors and measures the safety performance and effectiveness of the SMS processes in support of the AM's overall safety accountability. The AM chairs the SRB and comprises the Nominated Persons (NP) and other relevant managers. The SM communicates and presents to the AM all the pertinent information from the SMS to allow its review and decision-making based on safety data obtained from surveys, audits, FDM, Risk Management systems, Internal Safety Reporting Scheme, etc.

The NPs is a term that refers to a group of persons nominated by the AM and accepted by the authorities, with the accountability and responsibility for ensuring, in their defined operational areas, the management of safety and security risks to airline operations.

The SAG is established as a standing group with relevant expertise to assist and act on behalf of the Safety Review Board. The SAG reports to and takes strategic direction from the SRB and comprises managers, supervisors, and personnel from operational areas.

The SAG aims to:

- Monitor operational safety.
- Resolve identified risks.
- Assess the impact on the safety of operational changes.

- Ensure that safety actions are implemented within agreed timescales.
- Review the effectiveness of previous safety recommendations and safety promotion.

Departmental Safety Action Group is gathered when the nature of certain occurrences, hazards identified, or risks arising from Hi Fly's operational environment may call for specific meetings to be organized between the Safety Department and key operational areas such as CAMO, Flight Operations, and Ground Operations.

3.2. SMS at Hi Fly

As a licensed and certified airline with two AOCs issued by ANAC and TM-CAD, Hi Fly must meet the highest safety standards.

Hi Fly's SMS was developed based on meeting the standards of ICAO, EASA, national authorities, and IOSA as an IATA member to meet those standards.

Hi Fly has established, executed, and incorporated a Safety Management System (SMS) throughout the company. It ensures that all potential safety hazards are recognised and the risks associated are mitigated throughout Hi Fly's operations and activities.

As part of their SMS, Hi Fly uses Softcraft SMS software as their tool, enabling the organisation to meet the highest standards.

The primary objectives of Hi Fly's SMS are:

- Identify safety hazards in operations and all its activities.
- Ensure remedial action is implemented to control safety risks.
- Provide for ongoing monitoring and assessment of safety performance.
- Make continual improvements to the level of safety in operations and all its activities.

The SMS produces relevant analytical information and data for use by management and non-management personnel, as appropriate, to prevent accidents and incidents. In case of an event/trend, the organisation follows the scheme shown in Figure 15.

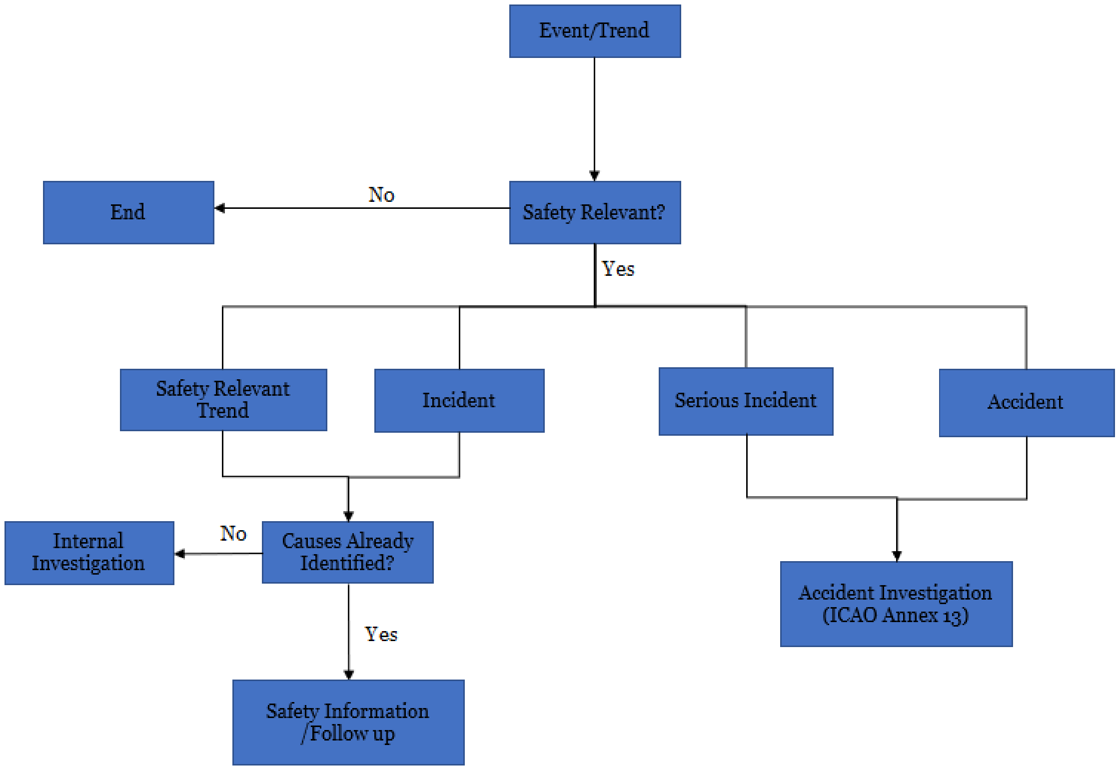

Figure 15 – Safety Relevant Information. Source: Adapted from [36].

3.3. Risk Assessment at Hi Fly

Hi Fly has implemented a comprehensive risk assessment process across all sectors to evaluate safety hazards and associated risks by considering potential negative outcomes. As the central coordinator, the Safety department ensures collaboration among various disciplines.

The adopted risk assessment methodology follows the widely recognised BowTie method. This approach presents a consolidated view of several plausible scenarios in a concise visual format. It offers a simplified and graphical representation of a risk, which would otherwise be challenging to articulate using alternative means.

3.3.1. Softcraft SMS

Softcraft SMS is an integrated software solution created by Softsegment that combines data from various sources and departments within an organisation to generate a unified overview of the organisation's safety status. According to [37], the software incorporates multiple modules to facilitate this process and provide an integrated view of the organisation's safety status. The software modules include:

- The Compliance Monitoring module serves as a quality management tool within the organisation, offering an auditor's perspective. Once the initial setup is completed, the module automates the management of all internal audits. Over time, the system gathers statistical data, providing management insights into root causes and trend analysis. This integration with risk assessment enables auditors and auditees to pre-assess the findings, making them visible to the Safety department, thus enhancing the organisation's understanding of its compliance performance.

- The Occurrence Reporting module aims to handle occurrence reports at the organisational level and assess their impact on quality and safety. It features a centralized structure for collecting and managing reported information from various sources, often interrelated. The module aggregates related information into cases, which may include the same event reported from different sources. Integration with risk assessment allows users to conduct pre-assessment risk evaluations for each event.
- The Risk Management module facilitates the management of identified risks within the organisation. These risks can stem from non-conformities identified in the compliance module, reports from safety events, hazards in the Hazard Register, and other sources. Mitigation strategies are implemented by defining a comprehensive set of necessary tasks, ensuring that the execution of these tasks leads to the desired reduction of risk levels.
- The Library Management module is designed to provide users with the most up-to-date versions of existing documentation. It involves the creation of publication lists and the addition of user groups. Whenever a new document is added to a list, all respective group users receive notifications. The system also keeps track of users who have accessed and acknowledged the new documentation and sends reminders to those who have not done so after a certain period.

4. Chapter 4 - Case Study

4.1. Introduction

The results for the most suitable risk assessment method for Hi Fly will be presented in this chapter, and the methodology used behind the decision-making.

It will present the definition of Multi-Criteria Decision Analysis (MCDA) and the reasons behind using the tool MACBETH. The software will be explained along with the logic and weights attributed to each area and indicator. Then, the outputs from the MACBETH tool will be presented.

4.2. Multi-Criteria Decision Analysis

The history of Multi-Criteria Decision Analysis (MCDA) dates back to the early 1960s when French mathematician Bernard Roy first introduced it. Since then, its role in different application areas has increased significantly, especially as new methods develop and as old methods improve [38].

Over seventy different MCDA techniques have been developed to facilitate the decision-making process in complex and ill-structured problems, focusing on resolving multiple and conflicting criteria, modelling preferences, and identifying compromised decision solutions [39].

MCDA is a decision-making methodology that helps decision-makers evaluate and prioritise alternatives based on multiple criteria or objectives. According to Barrico [40], cited by Raposo [41], the decision processes multicriteria are, for example:

“Choosing the site for the construction of a bridge, where the criteria can be the cost, the impact on the river itself (either environmental or in its use), traffic volume, impact on impact on the riverbanks, aesthetics, fare, etc.;”

“Finding the most economical routes to pick up/pick up products for the customers of a particular company, where the criteria can be time, distance, delay, traffic, etc.”

Considering these examples, a multicriteria decision problem requires the decision-maker to weigh the pros and cons of each criterion and consider how the different criteria interact. The decision-maker must balance the importance of each criterion and determine the relative weight or priority that should be given to each one. This process involves evaluating the alternatives against the criteria and synthesising the results to identify the best alternatives that meet the decision-makers objectives.

The potential benefits of the use of MCDA in planning projects are summarized in Figure 16.

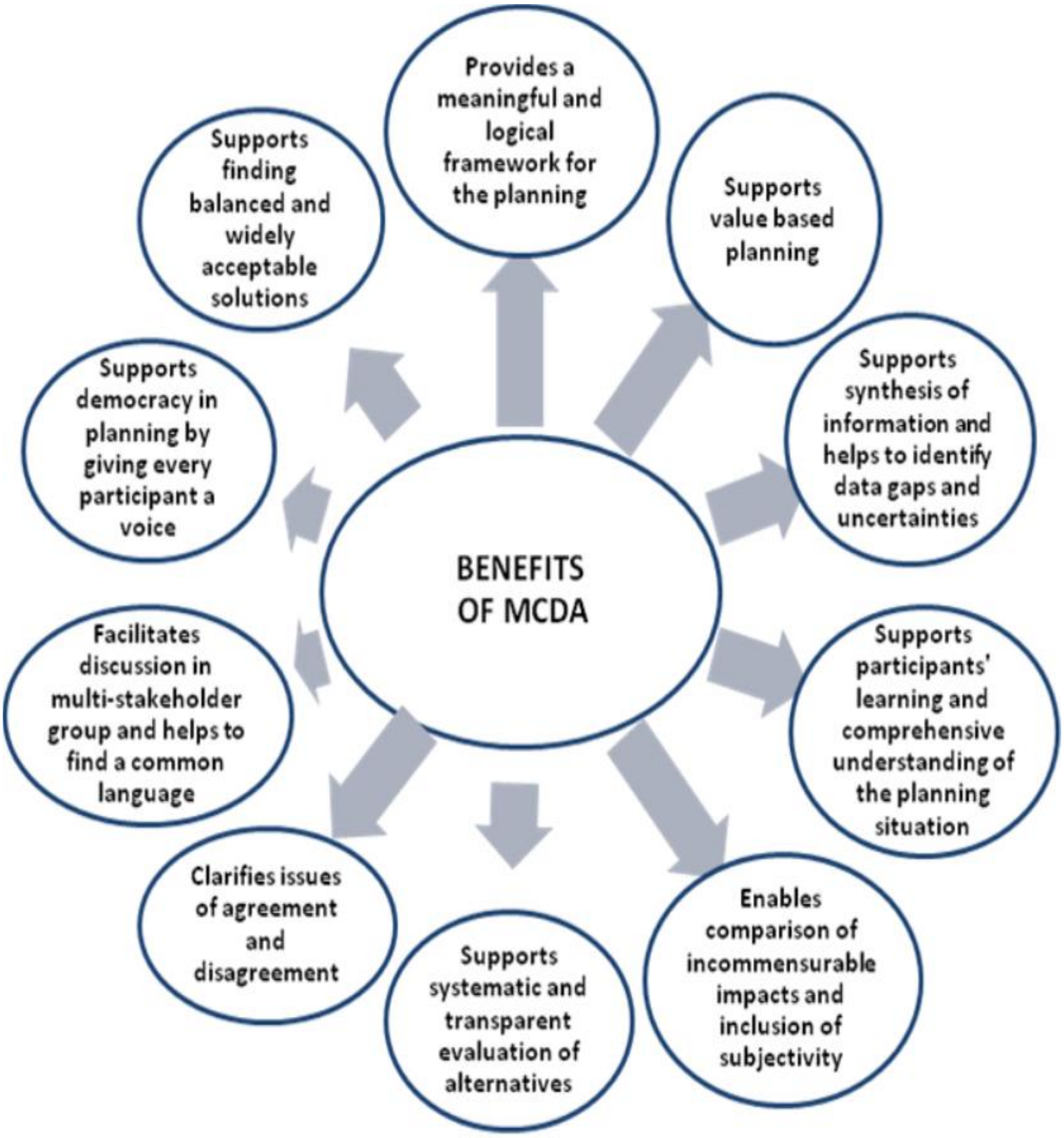

Figure 16 - Benefits of MCDA [42].

There are several MCDA methods available, and the choice of method depends on the specific decision problem and the decision-makers' preferences.

These methods are described in Table 25.

Table 25 – Methods Available for MCDA. Source: Adapted from [38].

Method	Advantages	Disadvantages	Areas of Application
Multi-Attribute Utility Theory (MAUT)	Takes uncertainty into account; can incorporate preferences.	Needs a lot of input; preferences need to be precise.	Economics, finance, actuarial, water management, energy management, agriculture
Analytic Hierarchy Process (AHP)	Easy to use; scalable; hierarchy structure can easily adjust to fit many sized problems; not data intensive.	Problems due to interdependence between criteria and alternatives; can lead to inconsistencies between judgment and ranking criteria; rank reversal.	Performance-type problems, resource management, corporate policy and strategy, public policy, political strategy, and planning.
Case-Based Reasoning (CBR)	Not data intensive; requires little maintenance; can improve over time; can adapt to changes in environment.	Sensitive to inconsistent data; requires many cases.	Businesses, vehicle insurance, medicine, and engineering design.
Data Envelopment Analysis (DEA)	Capable of handling multiple inputs and outputs; efficiency can be analyzed and quantified.	Does not deal with imprecise data; assumes that all input and output are exactly known.	Economics, medicine, utilities, road safety, agriculture, retail, and business problems.
Fuzzy Set Theory	Allows for imprecise input; takes into account insufficient information.	Difficult to develop; can require numerous simulations before use.	Engineering, economics, environmental, social, medical, and management.
Simple Multi-Attribute Rating Technique (SMART)	Simple; allows for any type of weight assignment technique; less effort by decision makers.	Procedure may not be convenient considering the framework.	Environmental, construction, transportation and logistics, military, manufacturing and assembly problems.
Goal Programming (GP)	Capable of handling large-scale problems; can produce infinite alternatives.	It's ability to weight coefficients; typically needs to be used in combination with other MCDM methods to weight coefficients.	Production planning, scheduling, health care, portfolio selection, distribution systems, energy planning, water reservoir management, scheduling, wildlife management.
ELECTRE	Takes uncertainty and vagueness into account.	Its process and outcome can be difficult to explain in layman's terms; outranking causes the strengths and weaknesses of the alternatives to not be directly identified.	Energy, economics, environmental, water management, and transportation problems.
PROMETHEE	Easy to use; does not require assumption that criteria are proportionate.	Does not provide a clear method by which to assign weights.	Environmental, hydrology, water management, business and finance, chemistry, logistics and transportation, manufacturing and assembly, energy, agriculture.
Simple Additive Weighting (SAW)	Ability to compensate among criteria; intuitive to decision makers; calculation is simple does not require complex computer programs.	Estimates revealed do not always reflect the real situation; result obtained may not be logical.	Water management, business, and financial management.
Technique for Order Preferences by Similarity to Ideal Solutions (TOPSIS)	Has a simple process; easy to use and program; the number of steps remains the same regardless of the number of attributes.	Its use of Euclidean Distance does not consider the correlation of attributes; difficult to weight and keep consistency of judgment.	Supply chain management and logistics, engineering, manufacturing systems, business and marketing, environmental, human resources, and water resources management.

[1]

Carlos Bana e Costa, Jean-Claude Vansnick, and Jean-Marie De Corte proposed a different approach to multi-criteria decision analysis that centres on the additive utility model.

[1] T.L. Saaty updated the Analytic Hierarchy Process (AHP) in 2005 where the disadvantages described in Table 25 where fixed.

In simpler terms, they suggested a new method that focuses on combining different criteria or factors in a way that is based on their relative importance or utility to the decision-maker. A result is a tool called MACBETH (Measuring Attractiveness by a Categorical Based Evaluation Technique).

4.2.1. Measuring Attractiveness through a Category-Based Evaluation Technique (MACBETH)

MACBETH is an approach to multicriteria decision aid whose development was set in motion in the early 1990s by C.A. Bana e Costa and J.C. Vansnick. The team expanded in subsequent years when it was joined by J.-M. De Corte [43].

The approach has been used in different contexts, such as developing scenarios and strategic plans for the textile industry, resource allocation in agriculture education, career choice benefits and risk maintenance.

MACBETH is a decision-making approach that enables evaluating options in a scenario involving multiple criteria. One of its key distinguishing features compared to other MCDA methods is that it requires only qualitative judgements about the relative attractiveness differences between pairs of elements at a time, which are used to derive the weights of the criteria and the numerical scores of the options for each criterion.

In simpler terms, it is a method that simplifies assessing the importance of different criteria and how well different options meet them by asking decision-makers to compare pairs of options at a time rather than trying to evaluate all options simultaneously [44].

MACBETH allows assigning ranks to each alternative directly or through pairwise comparisons of the elements to determine their relative attractiveness. Given two alternatives, the decision-maker should say which is the most attractive (and has the highest rank).

According to [43], MACBETH is a humanistic, interactive, and constructive approach:

- Humanistic – It can help decision-makers ponder, communicate, and discuss their value systems and preferences.
- Interactive – the reflection and learning process can best spread through socio-technical facilitation sustained by straightforward questioning-answering protocols.

- Constructive – it rests on the idea that full-bodied convictions about the kind of decisions that do not exist in the minds of the decision-makers help to form such convictions and build robust preferences considering the different options to solve the problem.

A summary of the steps involved in using MACBETH is given in Figure 17.

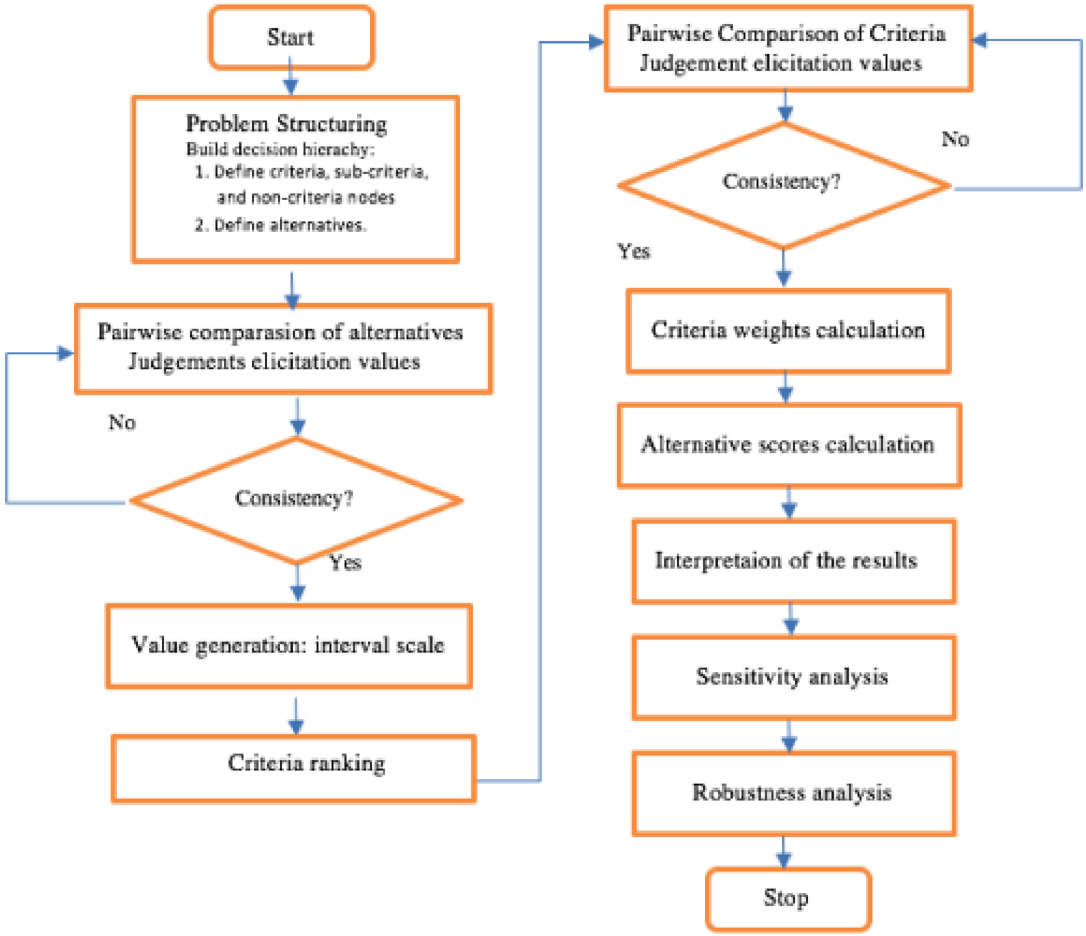

Figure 17 – MACBETH approach [45]

When evaluator judgements are set, their consistency is verified, and corrections may be needed to avoid inconsistencies if they arise. Then, MACBETH develops a quantitative evaluation from the evaluator's qualitative judgements.

For this quantitative evaluation model, a value scale is calculated for each criterion and its weight. Value scores are aggregated additively, considering all the criteria to calculate the overall value scores, reflecting their attractiveness.

The use of this tool is explained by the fact that with MACBETH, it is possible to accumulate more options and ways of thinking, thus increasing flexibility in decision-making.

4.3. Hi Fly Case

4.3.1. Key Performance Areas (KPAs) and Key Performance Indicators (KPIs) Assessment

It is necessary to define a set of Key Performance Areas (KPAs) and Key Performance Indicators (KPIs) that could give the most suitable risk assessment method for Hi Fly's operations. KPA represents the specific areas and domains that will be evaluated, while the KPI provides a measurable and quantifiable metric to track the progress towards a specific goal. These sets of KPAs and KPIs are not clearly defined by any authority [46].

In this case study, several domains are evaluated, including accuracy, applicability, effectiveness, risk capability, support and updates, and user-friendliness.

The KPAs are chosen based on literature reviews in line with the various documents issued by various authorities to meet the standards.

Each KPA is associated with two KPIs. These KPIs provide measurable indicators that will help assess the effectiveness and efficiency of each risk assessment method within each KPA.

4.4. Department Surveys

A survey was conducted in various departments (Safety, Compliance, Training, Security, CAMO, Ground Operations, Flight Operations and Dispatch) to gather quantitative data.

The survey aims to collect data to find the most relevant areas of a risk assessment method and the most important indicators of the BowTie method currently used in the organisation. The results will serve as inputs for the M-MACBETH software.

The survey consisted of two steps:

1. The first step was to rank the KPAs by relevance order, from the least relevant to the most relevant (number one represents the least relevant while number six represents the most relevant KPA). Each KPA should be assigned a unique rank, and different KPAs can be assigned the same rank in the relevance order.
2. In the second step, the responders needed to answer the questions, assigning only one score to each question.

This questionnaire was answered by the Safety Links of each department (Appendix A), while in the Safety department, it was answered by all members (Appendix B).

Table 26 represents an example of the survey design with a random relevance order, the KPAs associated with the relative KPIs, and the associated questions.

Table 26 - Design of the departmental survey example. Source: Own Elaboration.

Relevance Order	KPA	KPI	Question	Scale
1 represents the most relevant KPA and **6** the least relevant KPA	Accuracy	Hazard Identification	To what extent does the current method identify possible risks?	1- Not Aligned to 5- Very aligned
		Exactness	How accurately does the current method identify potential risks?	1- Not Accurately to 5- Very Accurately
	Applicability	Efficiency	Rate the overall efficiency of the current method?	1- Very Inefficient to 5- Very Efficient
		Standards	To what extent does the current risk assessment comply with industry standards, regulations, and best practices for HiFly's operations?	1- Not Compliant to 5- Very Compliant
	Effectiveness	Likelihood	How effective is the current method in identifying the likelihood of potential risks?	1- Not Effective to 5- Very Effective
		Perception	How well does the current method present the results and the outputs?	1- Not Well to 5- Very Well
	Risk Capability	Barriers and Mitigation Actions	Does the current RA method provide the capacity to assess and expose the barriers imposed and possible mitigation actions?	1- Limited to 5- Highly Comprehensive Coverage
		Severity and Impact	How well does the current method capture the criticality (severity) and impact of assessed risks?	1- Not Well to 5- Very Well
	Support and Updates	Frequency and Quality	How often does the current method receive updates or enhancements to address new operational challenges or industry changes?	1- Not Often to 5- Very Often
		Solidity	How solid and well-founded is the RA in your department?	1- Not Solid to 5- Very Solid
	User Friendliness	--	How user-friendly is the current method in terms of ease of understanding and implementation?	1- Not user-friendly to 5- Very User-friendly

Each KPA and their respective KPIs define the general guidelines a risk assessment must follow.

The accuracy assessment focuses on the method's ability to identify risks accurately, while applicability assesses its efficiency, suitability, and compliance with industry standards. The effectiveness area measures how well the method identifies risk likelihood and presents the results. In contrast, the area defined as risk capability evaluates the method's capacity to identify barriers, propose mitigation actions, and assess risk severity and impact. Support and updates examine how solid the method is and how frequently it has updates to address operational challenges and overall quality improvements. Lastly, user-friendliness assesses how easy it is to understand and implement the risk assessment method.

Each KPI is assigned a qualitative judgement scale ranging from one to five, with one representing the lowest level and five representing the highest level. The scale provides a framework for evaluating the alignment, accuracy, efficiency, compliance, effectiveness, perception, coverage, severity and impact, frequency, quality of the updates, and solidity of the risk assessment approach. This scale is a standardized method to measure and compare the performance of the risk assessment methods described in chapter 2.3, enabling the data needed for the M-MACBETH software to decide which risk assessment method is more suitable for Hi Fly's operations. The Safety department will be responsible for the qualitative judgements needed to complete the evaluation table, which will be described further.

4.4.1. Assigning Weights and Scores

The weighted rankings for each KPA can be calculated by assigning a weight to each rank on the relevance order. As described above, the KPAs are ranked from one (highest) to six (lowest) in the relevance order so that the weights will be assigned according to Table 27. The average weighted ranking can be determined by aggregating the results across all respondents.

The KPA with the highest average weight ranking signifies that, on average, respondents considered it to be the most relevant or important.

Table 27 – Relevance Order and their respective weights. Source: Own elaboration.

Relevance Order	Weights	
1	6	Highest
2	5	
3	4	
4	3	
5	2	
6	1	Lowest

4.5. M-MACBETH Software

M-MACBETH software is a tool used in the application of the MACBETH approach. It is designed to assist decision-makers and researchers conducting MCDA by providing a structured analysis process.

In the MACBETH approach, the M-MACBETH software facilitates the measurement of attractiveness by incorporating qualitative judgements of differences in attractiveness between options. It allows users to make qualitative judgements of attractiveness differences between two elements simultaneously, reducing the cognitive load of expressing preferences numerically. These qualitative judgements are used to construct a value function and generate value scores for the criteria. The software also supports the assessment of the attractiveness differences of a set of reference and hypothetical scenarios, enabling the determination of criterion weights through qualitative judgements. Ultimately, the software utilizes an additive model to calculate the total value scores of alternative options.

The software enables users to create a structured value tree, establish value functions, evaluate and assign scores to alternative options based on various criteria and perform sensitivity analysis on weights and performance data.

Many different factors define the quality of a risk assessment method (ability to identify hazards, determine the vulnerability, and mitigation actions, among others). It is crucial to find key performance areas and indicators to be the most accurate for the analysis. A crucial step is the choice of KPIs to structure the decision tree. Thus, to do an external benchmarking evaluation, the criteria must be in a complex form (output/input structure type). The value tree constructed in the M-MACBETH software is depicted in Figure 18.

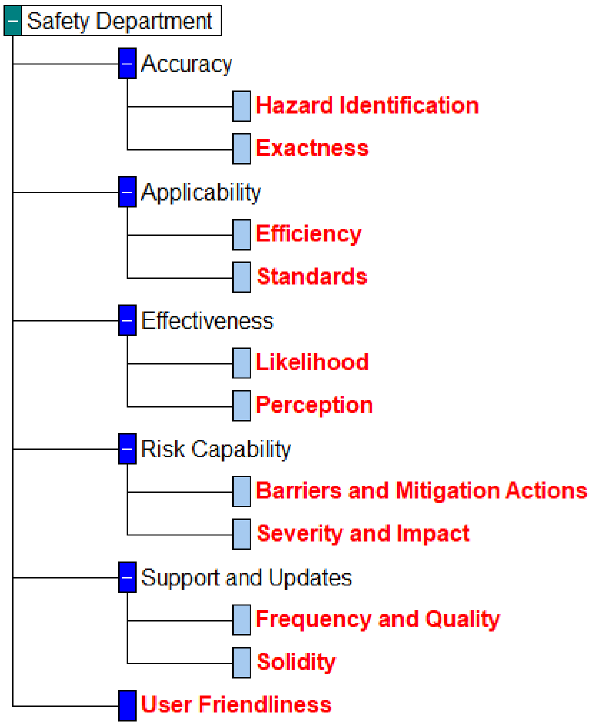

Figure 18 – Value Tree used in M-MACBETH. Source: Own Elaboration.

4.5.1. Evaluation

Each KPI will receive a qualitative judgement, converted into a numerical scale, as shown in Table 28.

Table 28 – KPIs qualitative judgement and correspondent numerical scale. Source: Own Elaboration.

Qualitative Judgement	Numerical Scale
Bad	1
Reasonable	2
Medium	3
Good	4
Very Good	5

According to the safety policy endorsed by the AM, the Safety department has the final say on safety-related decisions. The qualitative judgement falls to the responsibility of the members that make up the department, coupled with the increased knowledge of risk assessment methods used in the aviation industry.

The evaluation allows the creation of Table 29 (Evaluation Table), which represents the qualitative judgement from the Safety department to each KPI associated with each risk assessment method and aims to compare each KPI associated with the respective method directly.

Table 29 – Evaluation Table Example. Source: Own Elaboration.

	Identification	**Exactness**	**Efficiency**	**Standards**	**Likelihood**	**Perception**	**Prevention**	**Severity**	**Updates**	**Solidity**	**Friendly**
ARMS											
ERCS											
BowTie											
Confict Areas											
7 step											
FMEA											
RCA											
FTA											
BrainStorm											
Checklist											
Monte Carlo											

	Evaluate from 1 (lowest) to 5 (highest)
Identification	Identification of possible risks
Exactness	Accuracy on the identification of possible risks
Efficiency	Efficiency of the method
Standards	Comply with standards and legislation
Likelihood	Effectiveness of identifying the likelihood of potencial risks
Perception	The presentation and interpretation of the results and outputs
Prevention	Capacity to assess and expose barriers imposed and possible mitigation actions
Severity	Capture the severity and impact of assessed risks
Updates	How frequent does the current method receives updates or improvements for new operational challanges?
Solidity	How solid and well founded is the method?
Friendly	How user friendly is the method?

The data obtained from Table 29 is then introduced in the M-MACBETH software as a comparison base between the risk assessment methods, providing a table of scores and an overall thermometer.

The method with the highest score is considered the most suitable for the organisation.

4.6. Results

This section will show the overall most relevant KPAs, the better-scaled KPIs regarding the BowTie methodology, the evaluation table, and the most suitable method for Hi Fly.

Table 30 shows the average relevance and weights from each KPA obtained from the questionnaires to the various departments.

The percentage column provides a clearer indication of the results.

Table 30 – KPAs Departmental Survey Results. Source: Own Elaboration.

KPA	Average Relevance	Average Weight	Percentage
Accuracy	3.14	3.86	18.37%
Applicability	3.29	3.71	17.69%
Effectiveness	3.43	3.57	17.01%
Risk Capability	2.71	4.29	20.41%
Support and Updates	4.00	3.00	14.29%
User Friendliness	4.43	2.57	12.24%

From this table, the following conclusions can be drawn:

- The KPA with the most average relevance is the "Risk Capability," with a relevance of 20.41%.
- The KPA with the least average relevance is "User Friendliness," with a relevance of 12.24%.

Table 31 provides the average scale from each indicator regarding the BowTie methodology obtained from the questionnaires to the various departments.

Table 31 – BowTie Indicators from the Departmental Surveys. Source: Own Elaboration.

KPI	Average KPI Scale	Percentage
Hazard Identification	3.67	10.11%
Exactness	3.50	9.65%
Efficiency	3.14	8.67%
Standards	4.00	11.03%
Likelihood	3.29	9.06%
Perception	3.43	9.46%
Barriers and Mitigation Actions	3.57	9.85%
Severity and Impact	3.57	9.85%
Frequency and Quality	2.43	6.70%
Solidity	3.00	8.27%
User Friendliness	2.67	7.35%

- The BowTie methodology has its best indicator as the “Standards” meeting.
- The BowTie methodology has its worst indicators in “User Friendliness” and the frequency of the updates needed and the quality of those updates.

Table 32 shows the average relevance and weights from each KPA obtained from the questionnaire to the Safety department.

Table 32 – KPAs Safety Department Results. Source: Own Elaboration.

KPA	Average Relevance	Average Weight	Percentage
Accuracy	2.75	4.25	20.24%
Applicability	4.25	2.75	13.10%
Effectiveness	2.50	4.50	21.43%
Risk Capability	2.25	4.75	22.62%
Support and Updates	5.75	1.25	5.95%
User Friendliness	3.50	3.50	16.67%

The following conclusions can be drawn from Table 32:

- The most important area in a risk assessment for the Safety department is the "Risk Capability," with a relevance of 22.62%.
- The least important area in a risk assessment for the Safety department is the "Support and Updates," with a relevance of 5.95%.

Table 33 provides the average scale from each indicator regarding the BowTie methodology obtained from the questionnaire to the Safety Department.

Table 33 – BowTie Indicators from the Safety Department Survey. Source: Own Elaboration.

KPI	Average KPI Scale	Percentage
Hazard Identification	3.50	8.86%
Exactness	3.50	8.86%
Efficiency	4.00	10.13%
Standards	4.25	10.76%
Likelihood	3.25	8.23%
Perception	3.50	8.86%
Barriers and Mitigation Actions	3.75	9.49%
Severity and Impact	3.50	8.86%
Frequency and Quality	3.00	7.59%
Solidity	4.00	10.13%
User Friendliness	3.25	8.23%

- The BowTie methodology strengths are in meeting the "Standards", "Efficiency", and "Solidity".
- The weaknesses are predicting the likelihood of an event, user-friendliness and the frequency and quality of the updates.

The SM and the Safety Officer completed the evaluation table (Table 34). The numbers presented are an average between both answers. The software will introduce this table as a judgement between the risk assessment methods.

Table 34 – Evaluation Table Results. Source: Own Elaboration.

	Identification	Exactness	Efficiency	Standards	Likelihood	Perception	Prevention	Severity	Updates	Solidity	Friendly
ARMS	4	4	5	5	4	4	4	4	4	4	5
ERCS	5	5	5	5	5	2	5	5	4	4	2
BowTie	4	4	5	5	4	3	4	4	4	4	3
Confict Areas	5	4	5	5	4	4	4	4	4	4	4
7 step	4	4	4	5	4	3	4	4	4	4	4
FMEA	4	5	4	4	3	5	5	4	4	4	3
RCA	4	4	3	4	2	5	4	1	4	3	4
FTA	4	4	2	4	2	3	2	1	3	3	1
BrainStorm	3	2	2	3	2	1	1	1	3	2	4
Checklist	2	2	1	3	2	3	2	1	3	2	4
Monte Carlo	1	1	1	2	1	3	5	3	3	2	2

These values and the percentage of relevance of each KPI in the departmental survey (Table 31) define the criteria needed for the decision in the M-MACBETH software.

As previously mentioned, M-MACBETH software is responsible for interpreting the inputs, and through various mathematical formulas, the software provides the table of scores and overall thermometer. Table 35 represents the table of scores obtained.

Table 35 - Table of Scores M-MACBETH software

Options	Overall	Identification	Exactness	Efficiency	Standards	Likelihood	Perception	Prevention	Severity	Updates	Solidity	Friendly
Maximum	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
ERCS	4.37	5.00	5.00	5.00	5.00	5.00	2.00	5.00	5.00	4.00	4.00	2.00
Conflict Areas	4.30	5.00	4.00	5.00	5.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00
ARMS	4.27	4.00	4.00	5.00	5.00	4.00	4.00	4.00	4.00	4.00	4.00	5.00
FMEA	4.15	4.00	5.00	4.00	4.00	3.00	5.00	5.00	4.00	4.00	4.00	3.00
Bow Tie	4.04	4.00	4.00	5.00	5.00	4.00	3.00	4.00	4.00	4.00	4.00	3.00
7 step	4.01	4.00	4.00	4.00	5.00	4.00	3.00	4.00	4.00	4.00	4.00	4.00
RCA	3.38	4.00	4.00	3.00	4.00	2.00	4.00	4.00	1.00	4.00	3.00	4.00
FTA	2.63	4.00	4.00	2.00	4.00	2.00	2.00	2.00	1.00	3.00	3.00	1.00
Checklist	2.22	2.00	2.00	1.00	3.00	2.00	3.00	2.00	1.00	3.00	2.00	4.00
BrainStorm	2.14	3.00	2.00	2.00	3.00	2.00	1.00	1.00	1.00	3.00	2.00	4.00
Monte Carlo	2.13	1.00	1.00	1.00	2.00	1.00	3.00	5.00	3.00	3.00	2.00	2.00
Minimum	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

The option with the better overall score is the ERCS method, with a 4.37 overall rating on a scale from one (minimum) to five (maximum), while the Monte Carlo method is the least rated method with a 2.13 overall score.

The overall scores of the options can be visualised graphically through the overall thermometer shown in Figure 19.

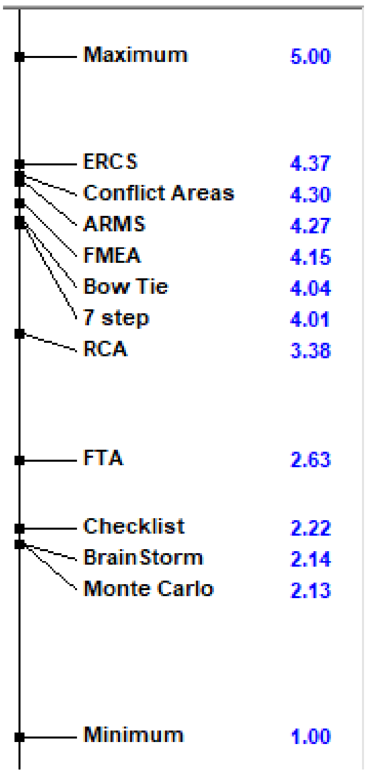

Figure 19 – Overall Thermometer for decision-making

4.7. Discussion

This section compares the results from the Safety department survey and the average results from the other departments. Also, the reasons to justify these results and the main takeaways will be discussed.

Table 30 suggests that the most valued area in a risk assessment method by each department is "Risk Capability". The results from the Safety Department survey (Table 31) confirm that "Risk Capability" is the most relevant area in the risk assessment method for the organisation. The justification for this result comes from the main goal of a risk assessment. A risk assessment aims to evaluate the risk present in the operation and create barriers to mitigate or eliminate that risk so the area of "Risk Capability" will be the most valued.

On the other hand, the least relevant KPA has different results when both surveys are compared. The Safety department considers the area "Support and Updates" the least relevant, while the other departments surprisingly consider the "User Friendliness" area the least important.

Analysing the tables, it is possible to conclude that the "Support and Updates" KPA is generally the least important in the organisation because, for the Safety department, it is clearly the least valuable with a very low score when compared to the other KPAs while for the other departments even if the "User Friendliness" KPA is the least relevant, it appears only two percentage points away from the "Support and Updates" area. A possible explanation for the "User Friendliness" KPA being rated so low in the other departments is that a risk assessment should be objective, effective, and not focused on the "human" part. Nevertheless, no method will provide good results if humans are not involved. If the platform is not friendly, it will not be used, which justifies the safety approach to this factor.

The KPA "Support and Updates" is generally the least relevant area due to the nature of operations that Hi Fly does. A well-founded and implemented risk assessment in the organisation facilitates the management of change needed for each new operation.

Regarding the KPIs, the "Standards" meeting of the BowTie method is generally the most valued in all departments.

Analysing both tables, it becomes clear that the BowTie methodology lacks user friendliness and frequent updates. These indicators show potential for improvement and the possible direction for implementing a new risk assessment method.

The similar results of both surveys demonstrate the organisation's safety culture. This similarity reflects that safety is the number one priority across all departments.

With the information gathered from the several tables and the M-MACBETH software, the ERCS method has the best overall score, making it the most suitable method for Hi Fly operations. The ERCS method stands out due to being the most complete method in the aviation industry. The methodology addresses the safety risk of an occurrence and not its actual outcome. It provides the identification of key risk areas, a harmonized approach for event severity and a probability determination based on the effectiveness of the stopping and remaining barriers.

4.8. Chapter Conclusion

The ERCS method scored 87.5 % of the maximum overall score. In comparison, the BowTie method scored 80.8%, but implementing such a complex method involves managing change and resources that currently don’t exist at the organisation due to the high volume of operations. Although the BowTie method is considered less suitable, it is by a small margin and meets all the regulations and safety standards, ensuring that the organisation thrives.

The similarity between the results of both surveys reveals a remarkable and consistent thread of thought across all departments. This unity in perspectives accentuates the holistic nature of the safety culture in the organisation.

5. Chapter 5 - Conclusions

5.1. Introduction

This final chapter concludes the dissertation with a synthesis, final thoughts and conclusions, and it also includes some of the limitations and difficulties encountered in carrying out this work. This study also suggests some improvements which could be implemented in future work.

5.2. Dissertation Synthesis

The dissertation comprises five chapters: introduction, literature review, SMS at Hi Fly, case of study and conclusions.

In the introduction (Chapter 1) of this dissertation, the focus lies on introducing the object in the study: the SRM inside an airline. The objectives are also presented in this chapter.

The main objective was achieved, as well as the secondary one. The most suitable risk assessment method for Hi Fly's operations was selected, and this dissertation brings together all the available information on risk assessment methods by describing the process and purpose of each method, providing a framework/ guideline, thus fulfilling the secondary objective. It also creates several KPAs, KPIs, and a judgement process based on the literature review that can serve as a basis for deciding which method is most suitable for airline operations.

The Literature Review (Chapter 2) delves into the current state of the art in SMS and risk assessment methods used in the aviation industry. An extensive literature review was conducted to gather information about the correct framework of an SMS model, focusing on the guidelines provided by ICAO in Doc 9859 entitled Safety Management Manual Fourth Edition. Also, in the second chapter, the risk assessment methods suitable for the aviation industry are described with the framework, the goals, and the flowchart needed to address it correctly.

In Chapter 3, Hi Fly's Safety Department organisation is described with a special focus on the responsibilities and obligations that the AM and the Safety Manager must fulfil. Also, all safety groups (SRB, Safety Link, NP, SAG and Departmental Safety Action Group) within the organisation are explained. Still, in Chapter 3, the primary objectives of Hi Fly's SMS, the scheme followed in case of a trend/event and the risk assessment implemented in the organisation are presented with special emphasis on the SMS tool used in the airline (Softcraft).

In the case study (Chapter 4), the MCDA is explained with examples showing the potential benefits and the several methods available. The selected technique, MACBETH, is then exposed, highlighting the framework of the tool. Then, the structure of the case study is presented with the introduction of the KPAs and KPIs, which are the backbone of the survey. The M-MACBETH software and the evaluation methodology are presented to fulfil the criteria needed to decide on the most suitable risk assessment method for Hi Fly. Still, in Chapter 4, the results from both surveys are discussed, the main conclusions are drawn, and the possible reasons behind them are explained. The conclusions on the results are taken to finish the fourth chapter.

In the dissertation's concluding chapter (chapter 5), the dissertation synthesis is presented, as well as concluding remarks which enable future research and work with the integration of more risk assessment methods and possibly AI into the aviation industry. It finishes with the prospects for future research and the final considerations in the conclusion section.

5.3. Concluding Remarks

In this dissertation, eleven risk assessment methods were evaluated. However, it is important to acknowledge that the vast and ever-evolving landscape of risk management encompasses many other potential methods that have regrettably been omitted from this study due to a lack of comprehensive literature review and empirical validation within the aviation context [47]. As the aviation industry continues to evolve, further research and exploration of these untapped methodologies are necessary to strengthen and broaden our understanding of risk assessment, ensuring the continuous improvement of aviation safety practices.

The human is the most flexible, adaptable, and valuable part of the aviation industry and vulnerable.

Over time, Human Factors have been systematically developed to enhance the safety of complex systems, such as aviation. This advancement involves cultivating an awareness of the predictable limitations of human capabilities and applying this knowledge to manage "human error effectively." Only by examining such errors from the vantage point of complex systems can the underlying causes leading to these errors be discerned and appropriately dealt with.

Frequently, organisational factors give rise to situations involving inadequate supervision, setting the stage for circumstances conducive to risky behaviours. Subsequently, these conditions pave the way for unsafe actions by operators. It is specifically at this stage, the point of unsafe operator actions, that the primary focus of most accident inquiries is directed.

The effectiveness of safety management hinges significantly on the extent of support from senior leadership and their dedication to fostering a work environment that maximises human performance. This environment should also foster active participation and contributions from personnel in the organisation's safety management processes. This approach facilitates a more careful and thoughtful risk assessment, continuously improving organisational safety.

The possible use of AI in aviation SMS holds immense potential to revolutionise how aviation safety is managed and enhanced. The capabilities of advanced computing techniques and AI to gather and analyse data from various sources in multiple languages within minutes enable qualified and objective risk assessments and provide a highly accurate global picture of the aviation environment. By processing and fusing diverse datasets, AI systems can identify patterns and potential risks more effectively than manual analysis, allowing for proactive measures to be taken. The real-time monitoring abilities of AI further empower aviation authorities and airlines to stay constantly informed about developments that might impact flight safety, enabling swift responses to sudden changes. As AI systems continuously learn and improve, the accuracy and efficiency of risk assessments will only grow over time, contributing to a safer and more secure aviation landscape. Embracing AI can lead to a new era of heightened safety and enable the industry to better adapt to emerging threats, fostering trust and confidence among passengers and industry stakeholders.

Ultimately, by incorporating human factors principles and AI development in the aviation industry, the risk assessments give a clear picture of all hazards involved, allowing organisations to strive to ensure safe and efficient operations while minimizing the chances of errors, incidents, and accidents.

5.4. Limitations

Identifying KPAs and KPIs for the risk assessment evaluation has posed significant challenges due to the lack of existing models or articles that can serve as a basis for comparison. Without established frameworks, the solution was based on legislation, guidelines from the authorities, and extensive research to create a customized set of relevant KPAs and KPIs. This demanding endeavour required thorough analysis and expert judgment, making it time-consuming and complex.

Additionally, obtaining valuable feedback for the survey proved to be a daunting task. The survey design required participants to reflect and provide thoughtful responses, which could not be rushed. However, due to the busy nature of daily work responsibilities, participants often faced time constraints, making it challenging to allocate sufficient attention to the survey. Unfortunately, in this case, it was impossible to assess all areas of the airline specifically the cabin department. Moreover, the timing of the survey, conducted during the summer when vacations were prevalent, added to a high volume of operations and did not facilitate the task. As people's availability varied, coordination became difficult, leading to delays and potential gaps in data collection.

5.5. Prospects for Future Work

The aviation industry has never been safer than it is today, but with the increased operations after the pandemic, some "safety steps" can be lost. Based on the limitations found in this work, the prospects for future work are as follows:

- Expand the questionnaires: to include more people from various departments to see if there are any differences in the results.
- Continuous Improvement: The risk assessment methods are an important element of the SMS, and with the emergence of new risks due to the high number of operations, risk assessments should strive to predict and mitigate possible hazards.
- Human Factor Consideration: Investigate the impact of human factors on the effectiveness of the selected risk assessment method, addressing potential challenges and offering mitigation strategies.
- Implementation: Implement and validate the chosen risk assessment method within the organisation's operations to assess its effectiveness and adaptability in real-world scenarios.

The use of AI in aviation SMS certainly opens the possibility of further work. With this comes many opportunities and challenges (hackers, leak of personal information) to the aviation sector.

5.6. Conclusion

This dissertation has achieved its set of objectives. It successfully identified the most suitable risk assessment method for Hi Fly operations and created a framework for future works on this topic. This dissertation followed the proposed methodology by identifying all the risk assessment methods suitable for the aviation industry. From here, it was necessary to use a decision support tool (MACBETH), which, with the right inputs, was able to find the best decision. These correct inputs started with setting a set of KPAs and KPIs to define comparisons and judgements between the methods. Then, it was necessary to create judgements and assign weights to each indicator for each method, and through the departmental surveys, it was possible to fulfil these requirements.

In conclusion, in the event of a change in the risk assessment method, the decision should be based on the ERCS method. Thus, this study showed that the difference in the overall score between the BowTie and ERCS methods is minimal, hence the non-mandatory change. Both methods are adequate, and the BowTie method fulfils the internal and external requirements of the legislation and demonstrates that the safety culture instilled in the organisation is very positive.

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Annex A – Event Risk Classification (ERC) from Aviation Risk Management Solutions (ARMS) Risk Assessment Template

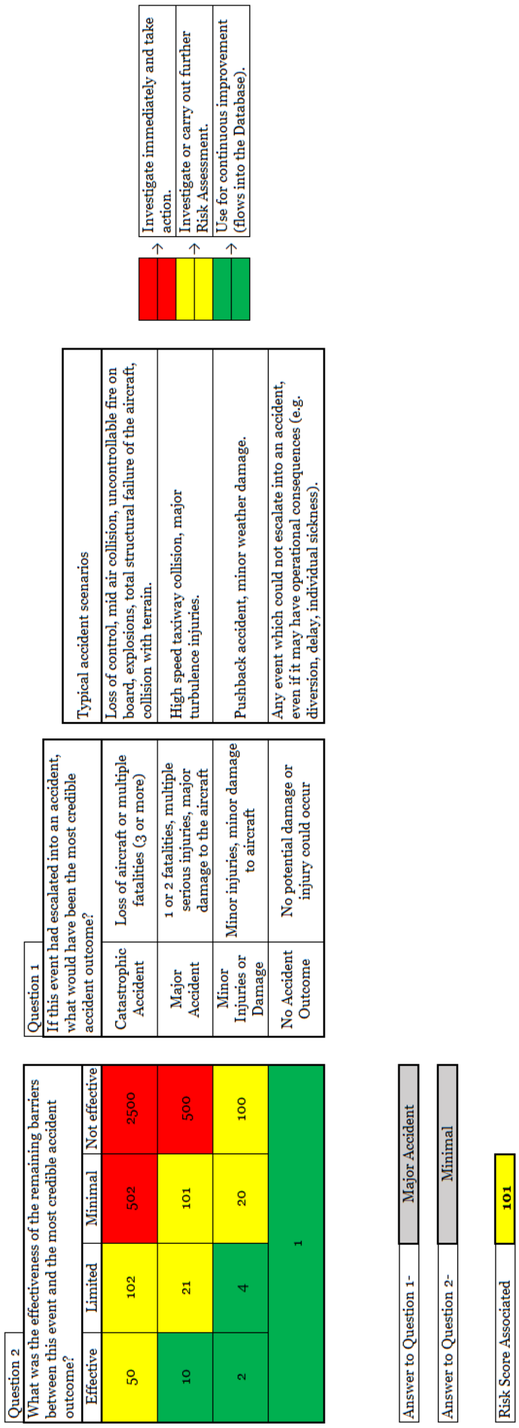

Figure AnxA 1 – ARMS Risk Assessment Template (ERC). Source: Own Elaboration.

Annex B – European Risk Classification Scheme (ERCS) Risk Assessment Template

Data	
Aircraft Registration and Type	A330-202,9H-HFH

ERCS	
Key Risk Area	Collision on runway, Ground Damage
Severity Score	M

Likelihood of escalition from the selected barriers		Selected barrier values	Values
1	Aircraft, equipment and infracture design	Failed assumed	5
2	Tactical Planning	Failed assumed	2
3	Regulations, Procedures, Processes	Failed assumed	3
4	Situational awareness and action	Failed assumed	2
5	Warning Systems operation and action	Failed assumed	3
6	Late Recovery from a potencial accident situation	Failed assumed	1
7	Protections	Failed assumed	1
8	Low energy Occurence	Remaining assumed	1

Risk Classification	
Barrier Weight Sum	0
Barrier Score	0
Risk Score	M0
Numerical Risk Value	100000

ERC Conversion	
Question 1	Not Effective
Question 2	Major Accident
Risk Score	500

Other Valuable Information	
Root Cause	
Event Type (SPI)	
Actual Occurence Date	30/09/2023
Actual Occurence Time	13:20:00
Occurrence Reported by	

Summing of Stop and Remaining Barriers
• All barriers scored using the values 'Stopped', 'Remaining Known' or 'Remaining Assumed' collect the points assigned to that barrier.
• A barrier that has 2 points assigned, and it is scored with one of the three before-mentioned values, these 2 points are added to the total sum.
• The same barrier scored with 'Failed Known', 'Failed Assumed' or Not Applicable' will have 0 points added to the total sum.

Figure AnxB 1– ERCS Risk Assessment Template. Source: Own Elaboration.

Annex C – BowTie Diagram Example

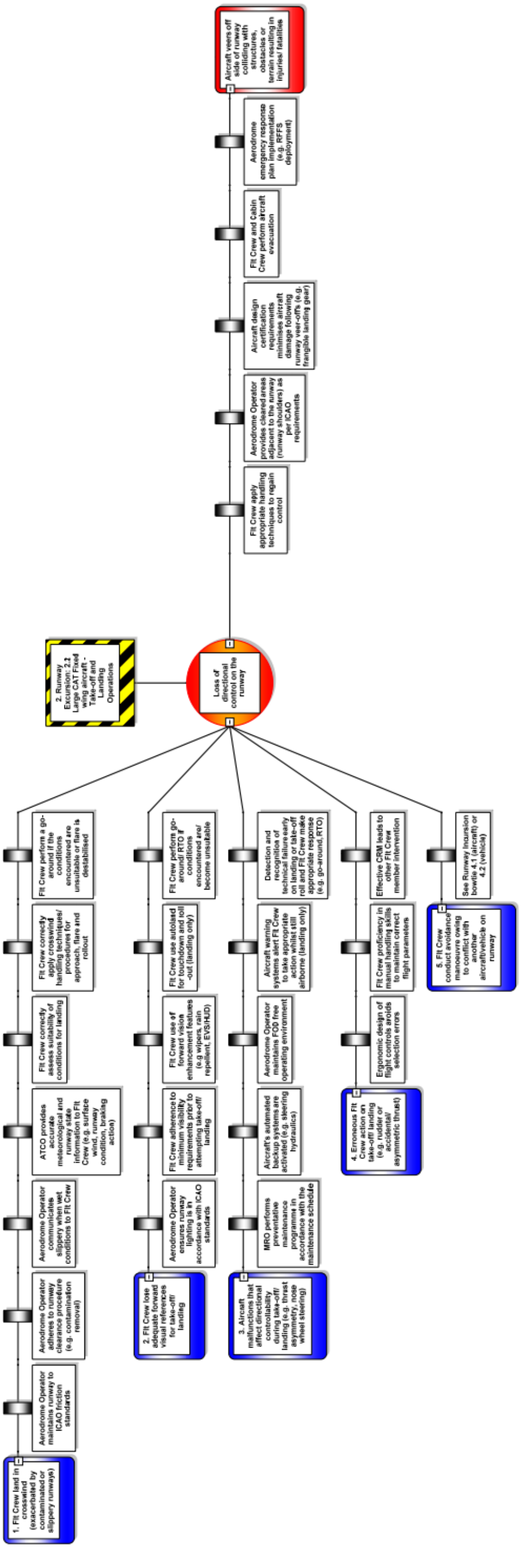

Figure AnxC 1 – BowTie Diagram [48].

Appendix A – Department Survey Answers

From Table ApA 1 to Table ApA 7, the answers from each respondent to the surveys made are depicted.

Table ApA 1 - Compliance Manager Survey

Relevance Order	KPA	KPI	Question	Scale
5	Accuracy	Hazard Identification	To what extent does the current method identify possible risks?	4
		Exactness	How accurately does the current method identify potential risks?	3
4	Applicability	Efficiency	Rate the overall efficiency of the current method?	3
		Standards	To what extent does the current risk assessment comply with industry standards, regulations, and best practices for HiFly's operations?	4
2	Effectiveness	Likelihood	How effective is the current method in identifying the likelihood of potential risks?	3
		Perception	How well does the current method present the results and the outputs?	3
3	Risk Capability	Barriers and Mitigation Actions	Does the current RA method provide the capacity to assess and expose the barriers imposed and possible mitigation actions?	3
		Severity and Impact	How well does the current method capture the criticality (severity) and impact of assessed risks?	3
6	Support and Updates	Frequency and Quality	How often does the current method receive updates or enhancements to address new operational challenges or industry changes?	2
		Solidity	How solid and well-founded is RA in your department?	2
1	User Friendliness	--	How user-friendly is the current method in terms of ease of understanding and implementation?	2

Table ApA 2 - Security Manager Survey

Relevance Order	KPA	KPI	Question	Scale
2	Accuracy	Hazard Identification	To what extent does the current method identify possible risks?	N/A
		Exactness	How accurately does the current method identify potential risks?	N/A
5	Applicability	Efficiency	Rate the overall efficiency of the current method?	3
		Standards	To what extent does the current risk assessment comply with industry standards, regulations, and best practices for HiFly's operations?	5
1	Effectiveness	Likelihood	How effective is the current method in identifying the likelihood of potential risks?	3
		Perception	How well does the current method present the results and the outputs?	4
4	Risk Capability	Barriers and Mitigation Actions	Does the current RA method provide the capacity to assess and expose the barriers imposed and possible mitigation actions?	3
		Severity and Impact	How well does the current method capture the criticality (severity) and impact of assessed risks?	4
3	Support and Updates	Frequency and Quality	How often does the current method receive updates or enhancements to address new operational challenges or industry changes?	2
		Solidity	How solid and well-founded is RA in your department?	N/A
6	User Friendliness	--	How user-friendly is the current method in terms of ease of understanding and implementation?	3

Table ApA 3 - CAMO Safety Reporting & Reliability Coordinator Survey

Relevance Order	KPA	KPI	Question	Scale
2	Accuracy	Hazard Identification	To what extent does the current method identify possible risks?	3
		Exactness	How accurately does the current method identify potential risks?	4
4	Applicability	Efficiency	Rate the overall efficiency of the current method?	2
		Standards	To what extent does the current risk assessment comply with industry standards, regulations, and best practices for HiFly's operations?	3
5	Effectiveness	Likelihood	How effective is the current method in identifying the likelihood of potential risks?	4
		Perception	How well does the current method present the results and the outputs?	4
3	Risk Capability	Barriers and Mitigation Actions	Does the current RA method provide the capacity to assess and expose the barriers imposed and possible mitigation actions?	4
		Severity and Impact	How well does the current method capture the criticality (severity) and impact of assessed risks?	4
1	Support and Updates	Frequency and Quality	How often does the current method receive updates or enhancements to address new operational challenges or industry changes?	2
		Solidity	How solid and well-founded is RA in your department?	1
6	User Friendliness	---------------------------------------	How user-friendly is the current method in terms of ease of understanding and implementation?	2

Table ApA 4 - Ground Operations Deputy Manager Survey

Relevance Order	KPA	KPI	Question	Scale
4	Accuracy	Hazard Identification	To what extent does the current method identify possible risks?	4
		Exactness	How accurately does the current method identify potential risks?	3
5	Applicability	Efficiency	Rate the overall efficiency of the current method?	3
		Standards	To what extent does the current risk assessment comply with industry standards, regulations, and best practices for HiFly's operations?	4
6	Effectiveness	Likelihood	How effective is the current method in identifying the likelihood of potential risks?	4
		Perception	How well does the current method present the results and the outputs?	3
2	Risk Capability	Barriers and Mitigation Actions	Does the current RA method provide the capacity to assess and expose the barriers imposed and possible mitigation actions?	4
		Severity and Impact	How well does the current method capture the criticality (severity) and impact of assessed risks?	3
3	Support and Updates	Frequency and Quality	How often does the current method receive updates or enhancements to address new operational challenges or industry changes?	3
		Solidity	How solid and well-founded is RA in your department?	4
1	User Friendliness	---------------------------------------	How user-friendly is the current method in terms of ease of understanding and implementation?	2

Table ApA 5 - NP Flight Operations Deputy Survey

Relevance Order	KPA	KPI	Question	Scale
1	Accuracy	Hazard Identification	To what extent does the current method identify possible risks?	4
		Exactness	How accurately does the current method identify potential risks?	4
3	Applicability	Efficiency	Rate the overall efficiency of the current method?	4
		Standards	To what extent does the current risk assessment comply with industry standards, regulations, and best practices for HiFly's operations?	4
4	Effectiveness	Likelihood	How effective is the current method in identifying the likelihood of potential risks?	3
		Perception	How well does the current method present the results and the outputs?	4
2	Risk Capability	Barriers and Mitigation Actions	Does the current RA method provide the capacity to assess and expose the barriers imposed and possible mitigation actions?	4
		Severity and Impact	How well does the current method capture the criticality (severity) and impact of assessed risks?	3
5	Support and Updates	Frequency and Quality	How often does the current method receive updates or enhancements to address new operational challenges or industry changes?	4
		Solidity	How solid and well-founded is RA in your department?	4
6	User Friendliness	--------------------------------------	How user-friendly is the current method in terms of ease of understanding and implementation?	4

Table ApA 6 – Flight Dispatch Supervisor Survey

Relevance Order	KPA	KPI	Question	Scale
3	Accuracy	Hazard Identification	To what extent does the current method identify possible risks?	4
		Exactness	How accurately does the current method identify potential risks?	4
1	Applicability	Efficiency	Rate the overall efficiency of the current method?	3
		Standards	To what extent does the current risk assessment comply with industry standards, regulations, and best practices for HiFly's operations?	4
4	Effectiveness	Likelihood	How effective is the current method in identifying the likelihood of potential risks?	3
		Perception	How well does the current method present the results and the outputs?	3
2	Risk Capability	Barriers and Mitigation Actions	Does the current RA method provide the capacity to assess and expose the barriers imposed and possible mitigation actions?	3
		Severity and Impact	How well does the current method capture the criticality (severity) and impact of assessed risks?	4
6	Support and Updates	Frequency and Quality	How often does the current method receive updates or enhancements to address new operational challenges or industry changes?	3
		Solidity	How solid and well-founded is the RA in your department?	3
5	User Friendliness	--------------------------------------	How user-friendly is the current method in terms of ease of understanding and implementation?	3

Table ApA 7 - NP Crew Training Survey

Relevance Order	KPA	KPI	Question	Scale	Corresponding Weight
5	Accuracy	Hazard Identification	To what extent does the current method identify possible risks?	3	2
		Exactness	How accurately does the current method identify potential risks?	3	
1	Applicability	Efficiency	Rate the overall efficiency of the current method?	4	6
		Standards	To what extent does the current risk assessment comply with industry standards, regulations, and best practices for HiFly's operations?	4	
2	Effectiveness	Likelihood	How effective is the current method in identifying the likelihood of potential risks?	3	5
		Perception	How well does the current method present the results and the outputs?	3	
3	Risk Capability	Barriers and Mitigation Actions	Does the current RA method provide the capacity to assess and expose the barriers imposed and possible mitigation actions?	4	4
		Severity and Impact	How well does the current method capture the criticality (severity) and impact of assessed risks?	4	
4	Support and Updates	Frequency and Quality	How often does the current method receive updates or enhancements to address new operational challenges or industry changes?	1	3
		Solidity	How solid and well-founded is RA in your department?	2	
6	User Friendliness	---------------------------------------	How user-friendly is the current method in terms of ease of understanding and implementation?	4	1

Appendix B – Safety Department Survey Answers

Table ApB 1 – Safety Officer Survey

Relevance Order	KPA	KPI	Question	Scale
5	Accuracy	Hazard Identification	To what extent does the current method identify possible risks?	4
		Exactness	How accurately does the current method identify potential risks?	4
4	Applicability	Efficiency	Rate the overall efficiency of the current method?	5
		Standards	To what extent does the current risk assessment comply with industry standards, regulations, and best practices for HiFly's operations?	5
3	Effectiveness	Likelihood	How effective is the current method in identifying the likelihood of potential risks?	4
		Perception	How well does the current method present the results and the outputs?	3
1	Risk Capability	Barriers and Mitigation Actions	Does the current RA method provide the capacity to assess and expose the barriers imposed and possible mitigation actions?	4
		Severity and Impact	How well does the current method capture the criticality (severity) and impact of assessed risks?	4
6	Support and Updates	Frequency and Quality	How often does the current method receive updates or enhancements to address new operational challenges or industry changes?	4
		Solidity	How solid and well-founded is the RA in your department?	4
2	User Friendliness	-------------------------------------	How user-friendly is the current method in terms of ease of understanding and implementation?	3

Table ApB 2 – FDM Analyst Survey

Relevance Order	KPA	KPI	Question	Scale
3	Accuracy	Hazard Identification	To what extent does the current method identify possible risks?	2
		Exactness	How accurately does the current method identify potential risks?	3
4	Applicability	Efficiency	Rate the overall efficiency of the current method?	4
		Standards	To what extent does the current risk assessment comply with industry standards, regulations, and best practices for HiFly's operations?	5
1	Effectiveness	Likelihood	How effective is the current method in identifying the likelihood of potential risks?	3
		Perception	How well does the current method present the results and the outputs?	5
2	Risk Capability	Barriers and Mitigation Actions	Does the current RA method provide the capacity to assess and expose the barriers imposed and possible mitigation actions?	4
		Severity and Impact	How well does the current method capture the criticality (severity) and impact of assessed risks?	3
6	Support and Updates	Frequency and Quality	How often does the current method receive updates or enhancements to address new operational challenges or industry changes?	4
		Solidity	How solid and well-founded is the RA in your department?	5
5	User Friendliness	-------------------------------------	How user-friendly is the current method in terms of ease of understanding and implementation?	5

Table ApB 3 - Deputy Safety Manager Survey

Relevance Order	KPA	KPI	Question	Scale
1	Accuracy	Hazard Identification	To what extent does the current method identify possible risks?	4
		Exactness	How accurately does the current method identify potential risks?	3
4	Applicability	Efficiency	Rate the overall efficiency of the current method?	4
		Standards	To what extent does the current risk assessment comply with industry standards, regulations, and best practices for HiFly's operations?	3
2	Effectiveness	Likelihood	How effective is the current method in identifying the likelihood of potential risks?	2
		Perception	How well does the current method present the results and the outputs?	2
3	Risk Capability	Barriers and Mitigation Actions	Does the current RA method provide the capacity to assess and expose the barriers imposed and possible mitigation actions?	3
		Severity and Impact	How well does the current method capture the criticality (severity) and impact of assessed risks?	3
5	Support and Updates	Frequency and Quality	How often does the current method receive updates or enhancements to address new operational challenges or industry changes?	2
		Solidity	How solid and well-founded is the RA in your department?	3
6	User Friendliness	--	How user-friendly is the current method in terms of ease of understanding and implementation?	2

Table ApB 4 - Safety Analyst Survey

Relevance Order	KPA	KPI	Question	Scale
2	Accuracy	Hazard Identification	To what extent does the current method identify possible risks?	4
		Exactness	How accurately does the current method identify potential risks?	4
5	Applicability	Efficiency	Rate the overall efficiency of the current method?	3
		Standards	To what extent does the current risk assessment comply with industry standards, regulations, and best practices for HiFly's operations?	4
4	Effectiveness	Likelihood	How effective is the current method in identifying the likelihood of potential risks?	4
		Perception	How well does the current method present the results and the outputs?	4
3	Risk Capability	Barriers and Mitigation Actions	Does the current RA method provide the capacity to assess and expose the barriers imposed and possible mitigation actions?	4
		Severity and Impact	How well does the current method capture the criticality (severity) and impact of assessed risks?	4
6	Support and Updates	Frequency and Quality	How often does the current method receive updates or enhancements to address new operational challenges or industry changes?	2
		Solidity	How solid and well-founded is the RA in your department?	4
1	User Friendliness	--	How user-friendly is the current method in terms of ease of understanding and implementation?	3

Appendix C – User Guide for a Risk Assessment in Softcraft-SMS

1.1. Overview

This document arises from the need to introduce the audience to the subject of risk assessment and the use of the Risk Assessment Module in Softcraft.

A Safety Management System (SMS) sits in four pillars: Safety Policy and Objectives, Safety Risk Management, Safety Assurance and Safety Promotion. This guide focuses on the Safety Risk Management pillar.

ICAO defines Risk Management as the identification, analysis, and elimination (and/or mitigation to an acceptable or tolerable level) of those hazards and the subsequent risks that threaten the viability of an organisation.

Risk Management aims to ensure that the risks associated with hazards to flight operations are systematically and formally identified, assessed, and managed within acceptable safety levels.

In the process of Risk Management, there are three steps considered essential: Hazard Identification, Risk Assessment and Risk mitigation.

1.2. Purpose of this guide

The primary objective of this guide is to provide users a clear understanding of the Softcraft Risk Assessment Module. The secondary objective of this guide is to provide the audience with general knowledge and familiarization with the subject of Risk Assessment, thus increasing the audience's awareness levels towards this theme.

1.3. Target Audience

This guide is intended primarily for users of Softcraft at Hi Fly and for use in a Safety Promotion and Safety Trainee environment.